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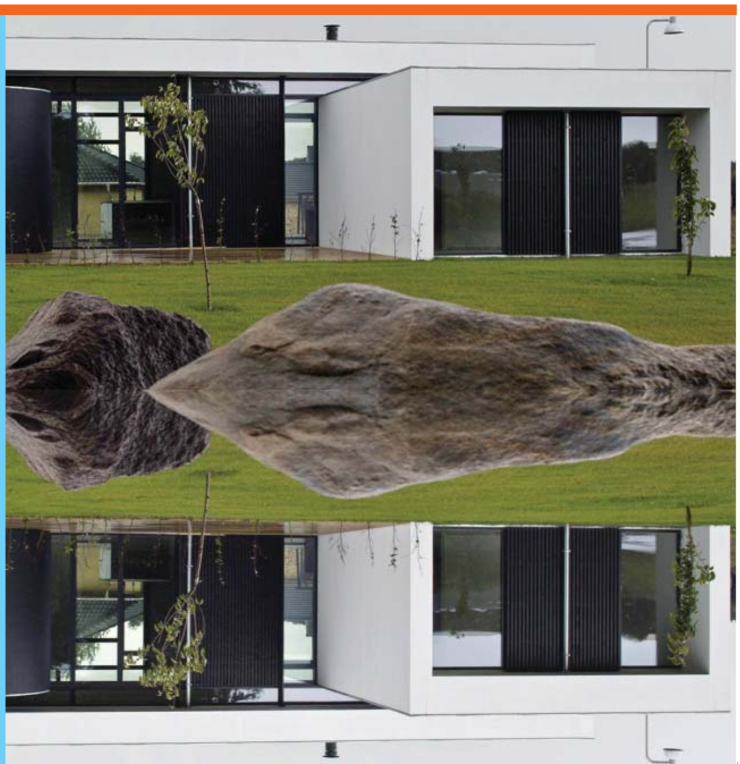
End-to-end requirements management for multi-projects in the construction industry

PhD Thesis



Michael Wörösch
DCAMM Special Report No. S162
February 2014

DTU Mekanik
Institut for Mekanisk Teknologi

End-to-end requirements management for multi-projects in the construction industry

by

Michael Wörösch

For fulfillment of the degree

Philosophiae Doctor

Department of Mechanical Engineering

Technical University of Denmark

February 2014

End-to-end requirements management for multi-projects in the construction industry

Michael Wörösch

Section of Engineering Design and Product Development
Department of Mechanical Engineering
Technical University of Denmark
Produktionstorvet, Bld. 426 B
DK-2800 Kgs. Lyngby
Denmark

PhD Thesis

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ABSTRACT

The research described in this PhD thesis focuses on the phenomenon that formalized requirements management, as many studies have shown, has yet to find its way into the construction industry, even though it is effectively used in other fields e.g. software development and the aerospace and defence industries. The research gives at the same time managers of construction projects a tool with which to manage their requirements end-to-end.

In order to investigate how construction companies handle requirements, a case project – a Danish construction syndicate producing sandwich elements made from High Performance Concrete and insulation materials – is used. By means of action research and interviews of case project staff it has become evident that many elements of formalized requirements management are missing in the case project. To fill those gaps and be able to manage requirements end-to-end a requirements structure is developed and tested as a starting point. This requirements structure is able to handle the encountered standard and non-standard situations such as product development and technology development in parallel with executing a construction project. At the same time the requirements structure is aimed at covering the entire life cycle of a building by considering future events.

However, the developed requirements structure is not enough for managing requirements. Therefore an intensive literature study on requirements management in general and in particular requirements management in construction is performed. The results of this literature study show that very little has been written about applying requirements management to the field of construction even though some authors have proposed to do so. This is a first indication that the entire field of construction lacks research with regards to requirements management.

As the literature study gives little new information, a series of interviews are initiated with experts from industry and universities. Those interviews reveal major shortcomings in the way requirements are handled in Danish construction companies today.

In order to give managers of construction projects a useful and guiding tool for formally managing requirements that is rooted in practice, the “Conceptual requirements management framework”, is created. The framework builds upon the gathered empirical data, obtained by action research, interviews, and available literature and is therefore inductive in nature.

The “Conceptual requirements management framework” is tested and validated by applying it to a building project and using additional methods of validation e.g. traces, extreme-condition tests, and face-validity.

The development and application of the requirements structure and the Conceptual requirements management framework mean that, for the first time structured requirements management and elements of systems engineering have been used in the construction industry. It is expected that

this approach counteracts some of the major challenges that are present in the industry by contributing to rework being avoided, shortened lead-times, less spending of resources, better quality, and a higher degree of satisfaction of stakeholders.

The results of the conducted research show that formal requirements management can successfully be applied to the construction industry that was examined. At the same time it is necessary to open doors to further research:

- The "Conceptual requirements management framework" has to be applied to additional building projects in order to gather more data for the improvement of the framework
- This research does not cover the long term effect of introducing requirements management to the construction industry and its customers. An investigation would be beneficial for the industry and academia

Key words: Requirements management, construction industry, conceptual framework, action research, interviews

RESUMÉ (IN DANISH)

Forskningen, som ligger til grund for denne ph.d.-afhandling, sætter fokus på det fænomen, at formaliseret kravstyring (requirements management), som mange studier har vist, endnu ikke har fundet vej ind i byggebranchen, på trods af at kravstyring bliver brugt indenfor andre fagområder som f.eks. softwareudvikling, luftfarts- og forsvarsindustrien med succes. Forskningen giver samtidigt ledere af byggeprojekter et værktøj til at håndtere krav fra projekt-opstart til afslutning.

Et dansk byggesyndikat, som producerer sandwichelementer fremstillet af højstyrkebeton og isoleringsmaterialer, anvendes som case for at forske i, hvordan byggefirmaer håndterer deres krav. Aktionsforskning og interviews af projektansatte tydeliggør, at casen mangler mange elementer af formaliseret kravstyring. Som udgangspunkt udvikles og afprøves en kravstruktur for at udfylde de manglende elementer samt være i stand til at håndtere kravene ”end-to-end”. Den udviklede kravstruktur er i stand til at håndtere, de i casen opståede, standard- og ikke-standard situationer, som f.eks. produktudvikling og teknologiudvikling, parallelt med udførelsen af et egentlig byggeprojekt. Samtidigt dækker kravstrukturen over hele livscyklussen af en bygning ved at tage højde for fremtidige begivenheder.

Den udviklede kravstruktur er et skridt i den rigtige retning, men viser sig at være utilstrækkelig til styring af samtlige krav. Derfor udføres et intensivt litteraturstudie om kravstyring generelt samt kravstyring specifikt indenfor byggebranchen. Resultaterne af dette litteraturstudie viser, at meget lidt er blevet skrevet om at anvende kravstyring indenfor byggeindustrien, selv om nogle forfattere har peget på behovet. Dette er den første indikation af, at der ikke bliver forsket nok indenfor kravstyring i byggeindustrien.

Da litteraturstudiet således kun giver få nye oplysninger afholdes en række interviews med eksperter fra byggeindustrien og universiteter. Disse interviews afslører klart, at danske byggefirmaer, stadig den dag i dag, håndterer kravene yderst mangelfuldt.

For at give ledere af byggeprojekter et nyttigt og vejledende værktøj til formelt at håndtere krav, der er forankret i praksis, udarbejdes værktøjet “Conceptual requirements management framework”. Dette rammeværk bygger på en kombination af afhandlingens empiri: data indsamlet ved aktionsforskningen og interviews samt tilgængelig litteratur. Derfor er rammeværket af induktiv karakter.

Værktøjet “Conceptual requirements management framework” testes og valideres ved at anvende det i et byggeprojekt samt ved brug af andre valideringsmetoder som f.eks. ”traces”, “extreme-condition tests” og ”face validity”.

Udviklingen og anvendelsen af kravstrukturen og Conceptual requirements management framework betyder, at der for første gang er blevet anvendt struktureret kravstyring og elementer af systems engineering i byggebranchen. Det forventes at denne tilgang bidrager til at undgå nogle

af branchens store udfordringer ved at minimere antallet af korrektioner, forkorte leveringstider, reducere ressourceforbrug, forbedre kvaliteten og opnå en højere grad af tilfredshed hos interessenterne.

Resultaterne af den udførte forskning viser tydeligt, at formel kravstyring kan anvendes i byggebranchen i Danmark og Schweiz. Resultaterne viser desuden et klart behov for yderligere forskning indenfor området. Det anbefales at:

- Det udviklede rammeværk anvendes på yderligere byggeprojekter for at indsamle mere data til forbedring af rammeværket
- Undersøge den langsigtede effekt af at indføre kravstyring på byggebranchen samt for dens kunder

Nøgleord: Kravstyring, byggebranchen, konceptuel rammeværksmodel, aktionsforskning, interviews

PREFACE

This PhD thesis documents the outcome of three years of research carried out at the Department of Mechanical Engineering at the Technical University of Denmark with Professor Niels Henrik Mortensen as supervisor. The PhD project has partly been sponsored by the Danish National Advances Technology Foundation and partly by DTU for which I am deeply grateful. The project was initiated in March 2011 and ended in February 2014. The project was not interrupted by any leaves of absence.

In hindsight I can now see that the seed for taking a PhD was planted around 15 years ago. During those 15 years I had been advancing from group leader to director and had the pleasure of running many complex and very expensive projects and programs. I noticed that the higher I climbed the ladder the less time there was for looking deeper into exciting aspects of engineering. This left me with a vacuum that I have now filled again. A motivation for taking on this particular PhD project was my extensive practical experience with requirements management in the sector of software development. I was at the same time curious to see how this experience could be put into play in the construction industry and thrilled about finding a solution to one of the practical problems I had had for many years – what is a good way for managing requirements on a project? A third reason for pursuing a PhD was my now deceased grandfather's question of "When are you pulling yourself together and becoming serious, boy?" At that time I realized that even though one is doing well in business many (academic) people do not consider this as an achievement. This impression has been confirmed several times during the past three years when talking to research staff at universities. Fortunately, I can see a changing focus towards being more business oriented at DTU. Hopefully this will continue and spread to other academic circles.

To be fair, I should also mention that some of the many people I have been interviewing in the construction industry consider academic people and their work as "close to useless" (direct quote of an interviewee). Perhaps it is time for them to start reading academic literature as many of the problems they have in their daily work have been described and solutions have been proposed there. With some luck, both people in industry and academia will change their views and might one day consider me a serious player.

One cannot undertake a PhD study without getting help along the way. I received a lot of support on my journey:

First of all I would like to thank Professor Niels Henrik Mortensen for being my supervisor and for showing confidence in my research. Thanks for taking decisions quickly, being willing to meet with professors from other universities, and for boosting my motivation on several occasions. Article writing can be a beast.

Professor Lars Hvam, my co-supervisor, deserves some gratitude, too. Thanks for helping me with some of the articles and telling me to "Focus, focus, focus!"

Additionally I wish to thank Associate Professor Thomas J. Howard for coming up with practical solutions in the darkest hours (in academia this seems to be the point where one of your journal articles gets outright rejected) and improving the "English" on some of my articles. I told you before: "I really like you, Tom."

One person who earned a special "Thank you!" is my friend Jens Gullberg-Hansen. His never ending optimism and looking at the positive side of things when obstacles arose contributed positively to this project. I am aware that I still have to tame my "impatient manager gene".

Karsten Bro, the manager of my case project, deserves my appreciation as well. Thanks for the nice days we had together on the connovate project and for helping me by providing needed documents and data and for showing me how to walk the extremely thin line between structure and chaos while being innovative.

Professor Gerhard Girmscheid has my gratitude for visiting me in Denmark, taking me to a conference in Australia, and giving me refuge at the ETH in Zurich during my external stay. Thanks for many good explanations and letting me use some of your contacts.

Special thanks go to all the people participating in the interviews. Thanks for helping me make the framework better, sharing data, and telling me how 'things are done in "reality"'.

Thanks to my co-authors, fellow PhD students, and the team of my case project. Our discussions and mutual reviews certainly had a positive influence on my work.

The following people are hereby recognized for doing a good job reviewing my thesis and challenging me on what I have written: Erling C. Havn, Hans Peter Lomholt Bruun, Poul Martin Ravn, Jens Gullberg-Hansen, Jonas Mørkeberg Torry-Smith, Karsten Bro, Nila Korzen, Steve Hart, Niels Henrik Mortensen, Ole Berard, Christian Brockmann, and Torben Anker Lenau.

To those who in any way have contributed to this PhD, but have not been mentioned above; consider this as my sincere thanks for your contribution, help and support.

Finally, I would like to express the deepest *thank you* to my family, Nila and Micas, for accepting me spending time on this PhD study and being abroad more than they have been used to. I know that missing his father was at times hard for my son, Micas.

Michael Wörösch

Lyngby, February 2014

“If you don’t know what you want, you end up with a lot you don’t”.

Chuck Palahniuk, American novelist

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1 INTRODUCTION

1.1 BACKGROUND AND PROBLEM AREA

Construction companies around the world are under a lot of pressure from their surroundings. They often operate in markets with small profit margins (in Denmark the profit margin of a main entrepreneur is typically only between 1% and 3% (Jespersen 2012) and interviewed Swiss companies stated profit margins of less than 5%) while they experience more and more global competition. This increased global competition can be seen in for example the increase of European tenders where construction companies have to undergo resource demanding bidding rounds instead of making a direct offer to a potential customer. Another weight on the shoulders of the construction companies is cheap foreign labour working for their competitors.

As if that was not enough the “clients of construction companies are also getting more sophisticated and requiring better project performance with greater customer satisfaction” (Yu and Shen 2013, p. 224 referring to Yu et al. 2009).

Additionally, the European Union (2008) dictates that buildings must produce less and less CO_2 and municipalities increase their obligations concerning ‘building green’ and safe.

One would assume that such conditions would motivate construction companies to increase productivity. But, as Kristensen in his PhD thesis (2011, p. 110) examined, the Danish construction industry has in a period of 40 years only managed to double its labour productivity whereas other industries have managed an increase of their labour productivity by a factor of 4 to 10. On top of that interviews conducted during this research project revealed that when building something ‘new’, i.e. something that has not been built by that particular company before, about 1/3 of the time spent on construction sites is idle time. Those interviews also showed that very few construction companies are using product platforms or apply the concept of modularization as a strategic tool.

As a consequence hereof – and admittedly a global recession – the number of construction companies in Denmark has gone down from about 36,000 in 2008 to an estimated 29,500 by the end of 2012 (Statistics Denmark 2012 and Danmarks Radio 2012).

Many of the above stated challenges could be counteracted, for instance by introducing formal requirements management to construction projects. The application of formal requirements management is known to lead to the following, general advantages (adopted from the Advice-Suite website 2013):

- The needs of the users are met
- Only important work is done
- Non-required functions are not developed
- Reduced waste of time

- Reduced waste of money
- No misuse of resources
- Money spent / invested is likely to provide return
- Decreased likelihood of bugs or errors

That those general advantages also apply to the construction industry and are expected to contribute to solving a persistent industry problem is confirmed by Fernie et al. (2003, p. 355), who state that ”the dominant storyline in the literature exhorts the adoption of requirements management with reference to a number of longstanding problems that are all too familiar to the construction industry: Failure to deliver projects within budget, late delivery of projects, failure to consider project decisions from a ‘whole life cycle perspective’, and poor customer satisfaction”. Unfortunately, as Fernie et al. (2003, p. 359) explain, requirements management cannot thoughtlessly be mapped from another industry and used in the construction industry as contextual differences do exist. These differences need to be considered.

It is acknowledged that formal requirements management is not a “universal cure” that solely solves all the above stated problems. Several other initiatives, for example the application of Building Information Modeling (BIM), risk management, general process improvements, resource simulators etc., are expected to positively contribute to improving the situation of the construction industry as well.

Yu and Shen (2013) agree with the fact that the use of formal requirements management in the construction industry is currently very limited and advocate introducing a systematic procedure to tackle the management of client’s needs and requirements.

So far the application of (formal) requirements management in the construction industry is limited (Barret and Stanley 1999, Kamara et al. 2002, Fernie et al. 2003) and little has been described about it in academic literature. This research reveals some of the reasons for not applying formal requirements management to the construction industry and examines how requirements are handled in some of today’s construction projects. Based on this insight, a generic framework that describes an end-to-end process that supports the formal management of requirements on construction projects is proposed.

Before submerging into this research topic it is necessary to define some of the key terms that are used throughout the thesis. This is done in the following section.

1.2 DEFINITION OF KEY TERMS USED

To achieve alignment with the reader the following terms need to be defined:

Conceptual framework: A network, or “a plane,” of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena (Jabareen 2009, p. 51)

Domain: A domain is a particular field of thought, activity, or interest, especially one over which someone has control, influence, or rights (Ordbogen.com 2014). A domain can also be defined as being equivalent to an engineering discipline (Torry-Smith 2013, p. 4)

End-to-end: After having analyzed the value chain of the case project (see Figure 17) I define end-to-end as: From the point when the customer places the order to the point of delivery

Effectiveness: The degree to which objectives are achieved and the extent to which targeted problems are solved. In contrast to efficiency, effectiveness is determined without reference to costs and, whereas efficiency means "doing the thing right," effectiveness means "doing the right thing." (BusinessDictionary.com 2014)

Framework: A structure for supporting or enclosing something else (TheFreeDictionary 2014). Even though the terms “framework” and “model” have different definitions in the context of this thesis they are sometimes used interchangeably

Implementation: To put into practical effect (TheFreeDictionary 2014)

INCOSE: Abbreviation for *International Council on Systems Engineering* (INCOSE 2011)

Innovation: An innovation is something original, new, and important – in whatever field – that breaks into (or obtains a foothold in) a market or society (my interpretation of Frankelius 2009)

Model: A thing used as an example to follow or imitate (Oxford Dictionaries 2014)

Multi-projects: Based on observations made during this research and experience gathered when managing projects I define “multi-projects” in the context of this thesis as: Several different kinds of projects that are related to each other e.g. by being targeted towards the same goal and run in parallel by the same organization, often by the same project manager

Product architecture: The scheme by which the function of a product is allocated to physical components (Ulrich 1995, p. 420)

Product platform: A set of subsystems and interfaces that form a common structure from which a stream of related products can be developed and produced efficiently (McGrath 1995, pp 294)

Requirement: Many definitions do exist. Due to its universal character the definition used in this thesis is: A condition or capability to which a project, product, service or system must conform

(Zielczynski 2008, p. 3). To give the reader more insight into the requirements that had to be managed on the case project and where those requirements originated from Article 1 is recommended. Some people divide requirements into hard and soft requirements. Hard requirements are requirements that can be directly measured and quantified; e.g. the dimensions of a wall. Soft requirements are then requirements that are difficult to measure and quantify directly; for example, the requirements for some personal attributes (creative thinking, communication…) that are needed by the project manager. In such cases a conversion is being done; one could measure the number of patent ideas that the project manager has during the course of a project instead of the more abstract “creative thinking”. Both types of requirements are important to consider

Requirements management: Also here several definitions exist. In the context of this research, requirements management means the *formal* management of requirements. The following two definitions are equally applicable: A systematic approach to eliciting, organizing, and documenting the requirements of the system, and a process that establishes and maintains agreement between the customer and the project team on the changing requirements of the system (Oberg 2000, p. 2). Or: Requirements management is the set of activities encompassing the collection, control, analysis, filtering, and documentation of a system’s requirements (Davis et al. 2000, p. 2)

Requirements management in construction: A special twist to requirements management in construction is that some of the requirements can be described in a visual way, e.g. a drawing or model. Otherwise the above stated definitions of requirements management apply. The construction industry has the special challenge that requirements are scattered across the many actors working together but having different agendas. Therefore conflicts often occur

System: An integrated set of elements, subsystems, or assemblies that accomplish a defined objective (INCOSE 2011, p. 5). Or: A system consists of a set of elements (subsystems) that possess properties and that are connected to each other by relationships. A system is separated from its surroundings by a system boundary and relates to its environment, for instance by input and output quantities. The function of a system can be described by those differences between its input and output quantities that correspond to its purpose (Ehrlenspiel 1994, p. 117)

Systems engineering: Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems (INCOSE 2011, p. 6)

In section 1.3 the aim and scope of the research are described and in section 1.4 the research questions are stated. Thus, sections 1.3 and 1.4 will proceed with further descriptions of the boundaries of the research elucidated in this thesis.

1.3 AIM AND SCOPE FOR THIS THESIS

At the beginning of this research project the scope was to help the case project to manage the different requirements that have to be handled when running a series of building projects. Those building projects had the goal of building single family houses made from high performance concrete sandwich elements.

Progressing through the project, it became clear that the case project was of a rather special nature and, apart from requirements originating from different building projects, requirements-wise many out of the ordinary situations had to be considered as well:

- Product development
- Technology development
- Product platform development
- Updating requirements of an existing product architecture

A more thorough description of the case project and its activities is given in section 4.

When asking experts at other construction companies that build single family houses and consulting domain literature, almost no help could be found on requirements management. Therefore the scope of this research was widened from helping one particular case project to developing a generic framework for formally managing requirements in (**at least the POL-2 part** (as explained on the next page)**, of**) the construction industry to be used by many project and requirements managers, if applicable. This generic framework should correctly be called "Conceptual Requirements Management Framework model" but will hereafter be abbreviated to "RMF". It is targeted at building projects of single family houses of up to two floors, large housing, and office buildings of up to 200,000 m^2.

The application of the RMF starts at the point when the project manager receives the order to run a project and ends at the point of delivery. What happens before, i.e. how the order is received, what type of contract is used (design-bid-build, design-bid-build with construction management, design-build, design-build-operate-maintain, build-operate transfer, integrated project delivery etc.), and what happens after delivery, e.g. operations, maintenance or transfer, are *not* within the scope of the framework. The scope of the framework is not limited to clients but tries to consider *all* stakeholders and phases of construction projects.

Even though the RMF was successfully applied to real building projects and positive results were achieved, as described in Articles 2 and 7, examining the effect of the framework is outside the boundaries of this research project, too, as the effect is expected to appear after the end of this research project.

Additional boundaries of this research are: The literature studies of this research had an international perspective, i.e. literature from many places of the world has been consulted for this research. **The empirical (practical) part of this research was primarily done in Denmark with the exception of a few interviews in Switzerland.** Therefore no claim can be made that the results of this research are applicable to any construction company in any country. Nevertheless the results might serve as a strong inspiration.

The interviewed companies were engaging in many different kinds of projects as described in section 4.2. Some of those companies offered pre-defined products and others were building according to a contract. But those were not the criteria for selecting the companies. The reason for selecting those companies for interviews was at first because they deliver single family houses of the same size as the case company. Based on the results of an analysis of those companies' requirements management (or lack of the same), later, medium-sized and large companies were also interviewed based on the hypothesis that large companies that run large and very expensive projects usually have a focus and processes as well as tools and databases in place, whereas small companies do not. Interviewing staff at a few small companies – down to as few as seven employees – was carried out to get this hypothesis confirmed.

No statistical criteria were applied when selecting the companies. Common sense was applied though.

Please note: The construction industry can be divided in many ways. Some of the many possible divisions that can be made are by: country / area, number of employees, turnover, type and category of construction projects, type of contract used, working for public or private customers, building according to requirements of the owner or offering a defined product, new build or refurbishment...

Alfen et al. (2014) have special focus on builders' merchants and what those have to be able to provide to construction companies. For that purpose they divide the construction industry into two poles – POL-1 and POL-2. POL-1 describes the part of the construction industry that builds according to the requirements of the owner (service provider, mainly using the design-bid-build type of contract). POL-2 describes the part of the construction industry that offers pre-defined products (e.g. a type of house or pre-fabricated elements). Most construction companies are within POL-1.

If such a division is made and applied to this research then the conclusion must be that the case project and the majority of the interviewed companies are within the POL-2 category. Therefore the gathered data is strongest in that category. Nevertheless, interviews of companies in the POL-1 category and companies operating both in POL-1 and POL-2 were also carried out. Data is available for both categories. But the data that was gathered in the POL-1 category is not as rich as the data obtained in the POL-2 category.

Here is an overview of the goals of this PhD project:

Research goals:

- Fill the gap of not applying formal requirements management to the construction industry (POL-2) by providing a generic process for managing requirements
  a) This process is targeted to be a generic framework for formally managing requirements in the construction industry that can be used by many project and requirements managers
  b) The INCOSE systems engineering handbook (INCOSE 2011) and PMBOK (PMBOK guide 2013) will be used as a base for the generic framework as those standards are being successfully applied for managing requirements in other industries. This is a goal and pre-requisite at the same time
- Provide evidence to support the claim that formal requirements management successfully can be used in the construction industry

Goals related to the case project:

- Help the case project to manage the different requirements that have to be handled when running a series of building projects
- Build a model that can help quantify the impact of new and changing requirements for an existing product architecture. This model is described in Article 4
- The RMF is targeted at single family houses of up to two floors, large housing, and office buildings of up to 200,000 m^2

Other goals:

- Initiate the moving of an entire field of business
- "Check the religion" of your research department. Members of my research department have continuously been advising construction companies to base their products on product platforms, as described by Meyer and Lehnerd (2011), to use clearly described product architectures (Ulrich 1995, Vezzetti et al. 2011), and apply the concept of mass customization (Pine 1999) where possible. Performing this "check" on the case project will provide further data to my research department

1.4 RESEARCH QUESTIONS

The title of this thesis is: End-to-end requirements management for multi-projects in the construction industry

The first research question is aimed at investigating the reasons construction companies have for not using formal requirements management. In this context it is important to understand the processes construction companies currently use for gathering and managing their requirements, the sources of requirements on construction projects, and what is being done in other industries concerning requirements management. The first research question (RQ) relates to this problem and is formulated as follows:

Main RQ1: What are the central challenges construction companies face when gathering requirements and managing them end-to-end?

In order to answer this question a structured process is formed around interviews, as described in section 2.2.2, and a literature review to claim generality. Further, a case study is performed to support the validity of the results. It is then natural to subsequently ask about the available solutions capable of addressing the phenomena. The second research question is hence formed around this problem:

Main RQ2: How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?

It is expected that answering the first two research questions will provide knowledge about a possible implementation of such a requirements management framework and that the first conclusions can be drawn about its prospects. The assumption is that formal requirements management can be used in the field of construction. This was triggered by Aslaksen (2006) who stated that systems engineering (requirements management can be considered as being part of systems engineering (INCOSE 2011, pp. 53)) equally applies to all industry sectors and disciplines. This includes the construction industry. Therefore, the third research question is formulated as follows:

Main RQ3: How can the developed requirements management framework be implemented and used on the case project?

Any research needs validation. The validation of the RMF is no exception to that rule. Therefore the fourth research question is put together with the motivation of testing the effectiveness and generalizability of the developed requirements management framework as well as its validation. Thus the fourth research question is phrased as:

Supporting RQ4: How can the effectiveness and generalizability of the requirements management framework be demonstrated and how can they be validated?

Due to the formulation of the research questions, two *research objects* can be defined. One object is the application of requirements management in the construction industry. The other research object is a new end-to-end framework that enables construction companies to apply formal requirements management to their projects. In section 2.1, the chosen research methodology is described to support the research process with the aim of answering the stated research questions.

*Please note: Research questions 1 to 3 are the main research questions whereas research question 4 is a supporting research question***.**

The “Chain of arguments” in relation to the research questions can be seen in Figures 1a and 1b. The “chain of arguments” describes the necessary steps to develop and validate the RMF. The figures also show the coverage of the research questions.

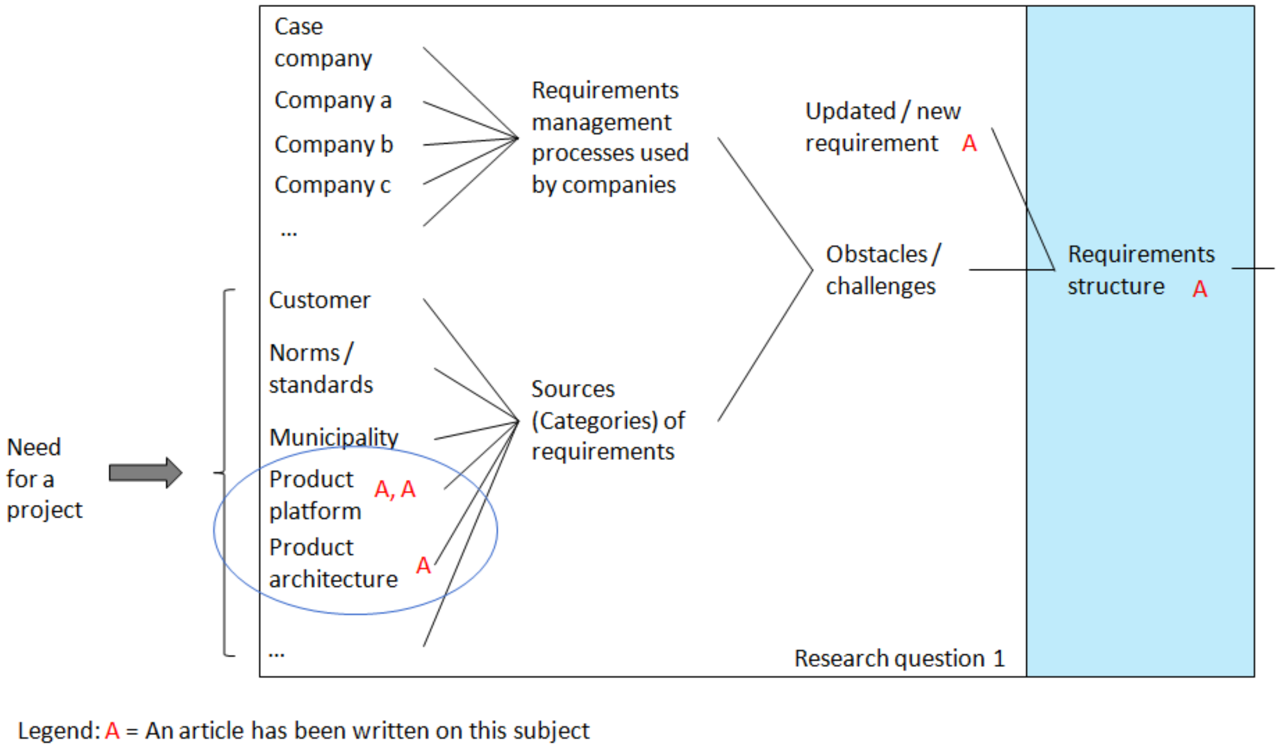

Figure 1a: “Chain of arguments” and coverage of the research questions

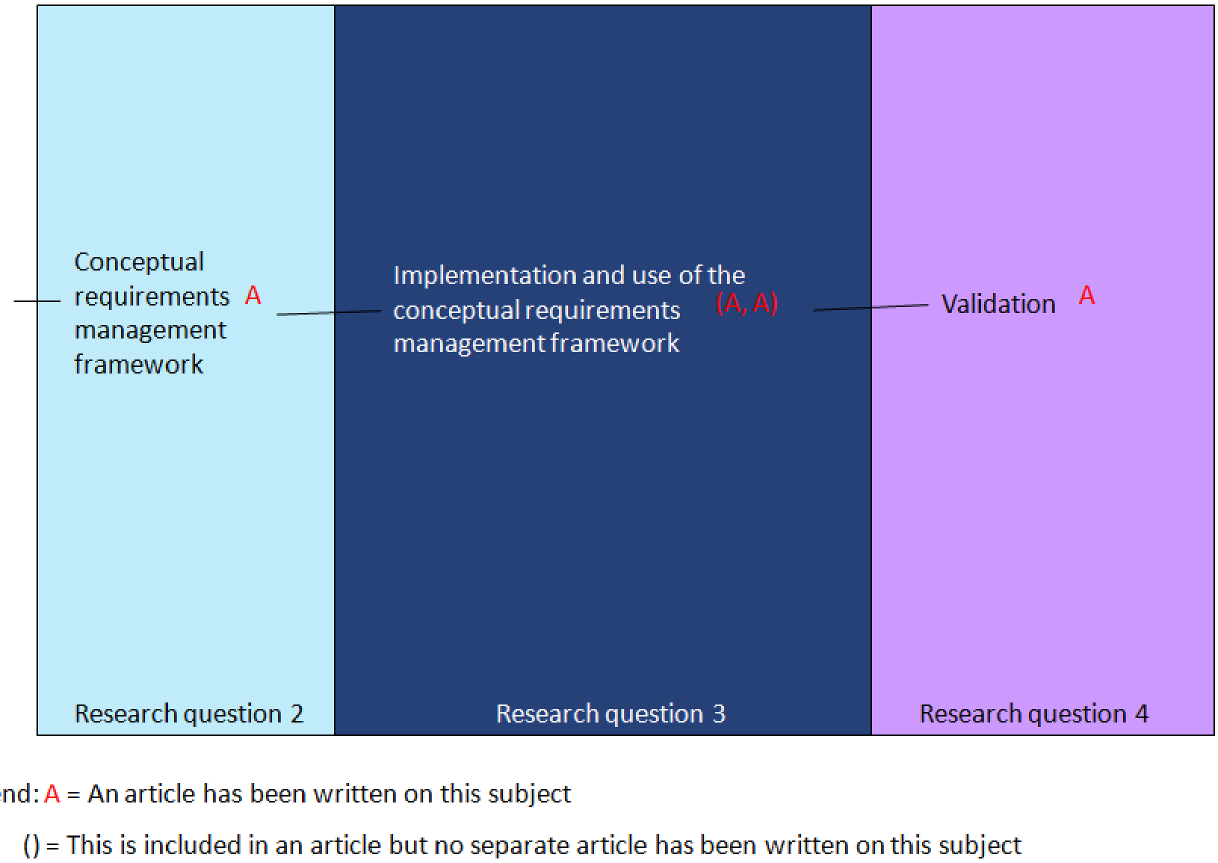

Figure 1b: "Chain of arguments" and coverage of the research questions – continued

To facilitate reading the thesis an outline is given in the following section.

1.5 OUTLINE OF THE THESIS

The introduction, section 1, contained the background for the research along with the definition of key terms, aim, scope, and research questions. The research approach is discussed in section 2. It contains the chosen research methodologies and the plan for the research. Section 3 provides an overview of the different theories used to form the basis for this research. The practical basis is described in section 4. Section 5 contains the results of the research. The results are presented via seven scientific articles labelled Article 1 to 7 and an additional sub-section. The conclusion is found in section 6, in which the research questions are answered. In the same section the achievement of the research goals is evaluated and implications on industry and society are discussed. Section 7 proposes future research and concluding remarks are made in section 8. References are listed in section 9. Appendices are found in section 10 and section 11 contains the scientific articles produced in this PhD project.

2 RESEARCH APPROACH

This section contains a description of the research methodology, research plan, and the steps that were followed when making and validating the RMF. The section gives a brief introduction to the articles that were written during this PhD project, how they relate to each other, and a mapping showing the coverage of the research questions by the different articles.

2.1 RESEARCH METHODOLOGY

The research conducted during this PhD project is of a qualitative nature. According to Dahler-Larsen (2007, p. 322) there are three main reasons for using the qualitative method: (1) the area of study is still relatively unexplored, (2) the area of study is composed and complex, or (3) the area of study is part of a cultural construction that has been created by the area of study itself. All three main reasons are applicable to this research.

Within the qualitative method the research methodology used in this PhD project was action research as it "aims to contribute both to the practical concerns of people in an immediate problematic situation and to the goals of science by joint collaboration within a mutually acceptable ethical framework" (Rapoport 1970, p.499) or as Checkland and Holwell (1998, p. 14) express it: "The researcher enters a real-world situation and aims both to improve it and acquire knowledge". The "real-world" situation of this research was provided by a case project and a series of interviews.

Moving from specific observations, i.e. a case project, to broader generalizations and theories means that this research is inductive in nature. Using the inductive approach has the risk that the research findings are only applicable to the observed case project and not to other projects. To mitigate this risk the results of this research have been presented to industry experts working at other companies and universities. Their feedback was then considered when detecting patterns and formulating hypotheses.

"Action research originates primarily in the work of Kurt Lewin and his colleagues and associates. In the mid-1940s, Lewin and his associates conducted action research projects in different social settings" (Coughlan and Coghlan 2002, p. 223) "in which they were concerned with and combined the generation of theory and the change of a specific situation through the participation of a researcher. The researcher acted on and in the system, and, the act itself is presented as the means of both changing the system and generating critical knowledge about it" (Middel et al. 2006, p. 70). Since then action research has been applied to different areas such as organization development (French and Bell 1999) and socio-technical work (Trist and Murray 1993).

There are different forms of action research (e.g. the number of phases carried out by the action researcher and system differ (Susman and Evered, 1978)) but several broad characteristics define action research (Middel et al 2006, Gummesson 2000):

- Research *in* action, rather than research *about* action
- Participative
- Concurrent with action
- A sequence of events and an approach to problem solving

Action research is cyclic. Coughlan and Coghlan (2002, pp. 230) offer a good description of how an action research cycle is built up. According to them a cycle consists of: (1) A pre-step – to understand context and purpose; (2) six main steps to gather, feed back and analyze data, and to plan, implement, and evaluate action; (3) a meta-step to monitor. Figure 2 shows a visual description of an action research cycle as defined by Coughlan and Coghlan (2002).

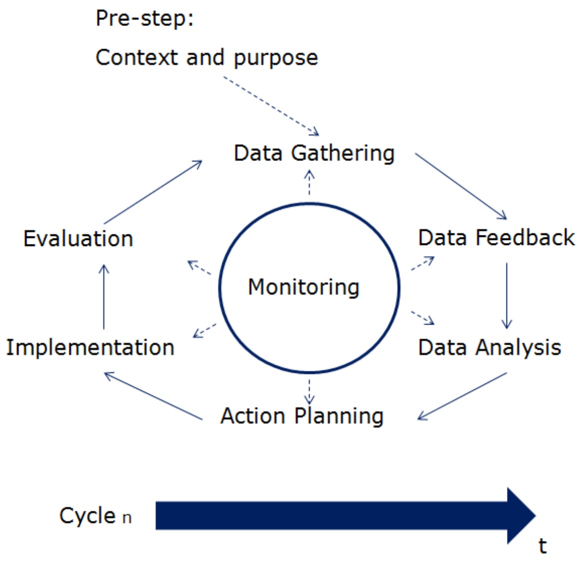

Figure 2: Action research cycle as defined by Coughlan and Coghlan (2002, p. 230)

The action research performed in this PhD project consists of one pre-step and four action research cycles. Those are described in the research plan (section 2.2). As this research was conducted on a case project, Yin (2009) and Voss et al. (2002) were used as sources of inspiration and knowledge. Furthermore Yin was used to get a better understanding of the boundary between action research and case study.

2.1.1 ROLE OF THE RESEARCHER

The main task of the researcher on the case project was to implement formal requirements management by finding a suitable structure that could contain all requirements of the case project in one place and to develop a requirements management framework based on that work. As Schein (1999) describes it I was acting as an external helper to the client system. When helping I was mainly using the ”process consultation model” as opposed to the “doctor-patient model”. In the ”process consultation model” the helpers work in a facilitative manner to help the client look into their own issues and create and implement solutions (Schein 1987, 1995 and Coghland 1994).

During the three years the project lasted I had full access to all key people and complete insight into all documents relevant to this research; including documents containing the future strategy of the case company and its products.

Another task I had was conducting interviews with the staff allocated to the case project as well as industry and university experts. This was, in my opinion, the most suitable method for gathering knowledge and overcoming the issue of formal requirements management not being used in construction on the case project — as it quickly and directly provided a state-of-the-art overview of how requirements are managed in the field of construction in Denmark.

The active participation in the case project has created project results that were checked by the project staff and approved by the project manager and the project steering group. It also ensured the active participation of the client.

Critique: This was the first time I had to implement formal requirements management without having a team to back me up from the very beginning. This situation changed over time as project staff was educated in formal requirements management. It was also the first time I had to implement requirements management in a to me unknown field of business and describe my work academically.

The active participation in the case project has influenced project staff and project results. An example of that is that I have spent one day a month with the project manager of the case project discussing all sorts of project management issues – but mainly the ones related to requirements management. This active “intervention” has altered the course of the case project. As this is action research this is a desired effect as it leads to a specific problem being solved. I am aware that other researchers are against action research for exactly that reason. The advantages and disadvantages of action research can be found in academic literature (Coughlan and Coghlan 2002 and many others) and will therefore not be discussed here. On a personal note, I would like to add that action research has been chosen as it seemed to be the most suitable methodology for this research project but I am not religious about the use of action research.

2.2 RESEARCH PLAN

This section presents the research plan for the PhD project and how it was executed.

2.2.1 ACTION RESEARCH

The action research on this PhD project was done in one pre-step and four action research cycles. This is visually shown in Figure 3:

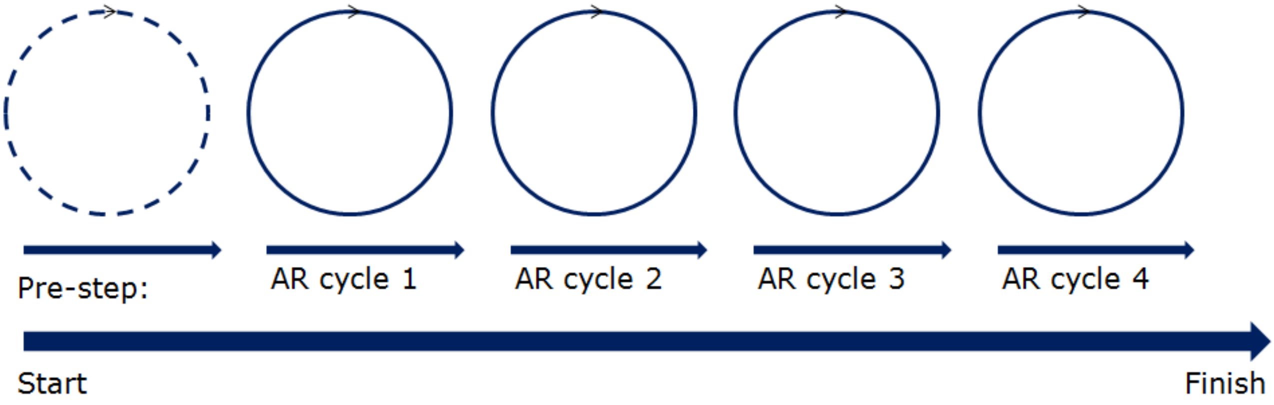

Figure 3: The action research cycles of this PhD project

The content of the pre-step and different action research cycles was as follows. Unless stated otherwise all bullet points are related to the case project:

Pre-step: Get the overview

- Understand context and purpose
- Conduct interview round 1 – with main focus on interviewing already known stakeholders
- Analyse answers of interview round 1 and make a document containing the combined answers of interview round 1

Action research cycle 1: Identify stakeholders and goals. How is requirements management done on the case project today?

- Establish communication with key stakeholders
- Define the high level project goals and product platforms that are supported
- Analyse the complete value chain – including an analysis of the customers
- Make project participants aware of formal requirements management and explain what it is about
- Find out which requirements are not covered by norms and standards
- Conduct interview round 2 – with main focus on members of the case project and industry experts
- Analyse answers of interview round 2 and add to document with the combined answers

Action research cycle 2: Make a detailed requirements structure for the case project

- Define a detailed product platform strategy
- Map all requirements into an xls. sheet
- Map requirements to goals
- Define all other criteria that are relevant for the xls. sheet (columns, headlines…)
- Analyse the combined documents and propose further actions / strategies
- Integrate requirements and other findings with time schedule (Work Packages) and risk management
- Conduct interview round 3 – with main focus on new key members of the case project
- Analyse interview round 3 and add the answers to the existing documents
- Figure out what can be done to make other construction companies use formal requirements management

Action research cycle 3: What are other construction companies doing? How can formal requirements management best be introduced to the staff of the case project and field of business?

- Conduct interview round 4 – with main focus on interviewing other construction companies
- Analyse interview round 4 and add the answers to the existing documents
- Find out what can be done to generally apply formal requirements management to the field of construction?
- Identify gaps and define missing product goals
- Commit to product platforms and other vital elements found during the analysis
- Refine requirements regularly
- Implement / apply formal requirements management
- Train certain members of the project in the use of formal requirements management

Action research cycle 4: Validate the implementation of formal requirements management on the case project and the framework

- Conduct interview round 5 – with main focus on interviewing potential users of the found solution (most likely a framework); use this as the main validation of your research
- Analyse interview round 5 and add the answers to the existing documents
- Refine the requirements further
- Examine whether formal requirements management has really been implemented / is being used
- What are the Lessons we have Learned?
- Are there any results / benefits?

All steps of all action research cycles were done together with the client. A close cooperation with and involvement of the client is crucial in action research (Coughlan and Coghlan 2002).

The reason for choosing four action research cycles was an anticipated time limit of two years. Each cycle was expected to take six months. On top of that were the pre-step and the dissemination of this research. Both were scheduled to last six months each.

2.2.2 INTERVIEWS

45 research interviews were conducted during this PhD project. Six of those interviews were semi-structured, meaning they had a flexible and fluid structure, allowing new ideas to be brought up during the interview as a result of what the interviewee said. This approach was helpful when developing the questionnaires. All others were structured. Except for two interviewees, all interviewed persons were either members of the case project or experts from the industry or universities. The remaining two interviews were held with people who had moved into buildings that were erected by the case company. Those two interviews were carried out to completely cover the value chain of the case project (Figure 17). As special rules apply to research interviews, guidelines provided by Kvale (1994) and Girmscheid (2007) were applied. As I am an engineer and experienced manager myself, who has been running projects, programs, and departments, I would label the interviews with the experts from the industry "*Expert peer interviews*" as was recommended by Brockmann (Hochschule Bremen, University of applied sciences) in a discussion about how to conduct research interviews with experts that can be considered "peers", i.e. managers and project managers with more than 10 years of experience and a background in engineering, in May 2013. Being treated as a peer was especially helpful when going through the requirements management processes of the different companies.

Concerning the evaluation of the interviews: The interviews were not transcribed, instead the minutes of each meeting were made and then reviewed and approved by the interviewee. As the interviews were built up in the same way (see Appendixes 1 to 3) it was fairly easy but time intensive to compare the different interviewees' answers to the same questions. Based on the differences and commonalities in the answers, conclusions have been drawn.

A visual overview showing the conducted interviews in relation to the elapsed time can be seen in Figure 4.

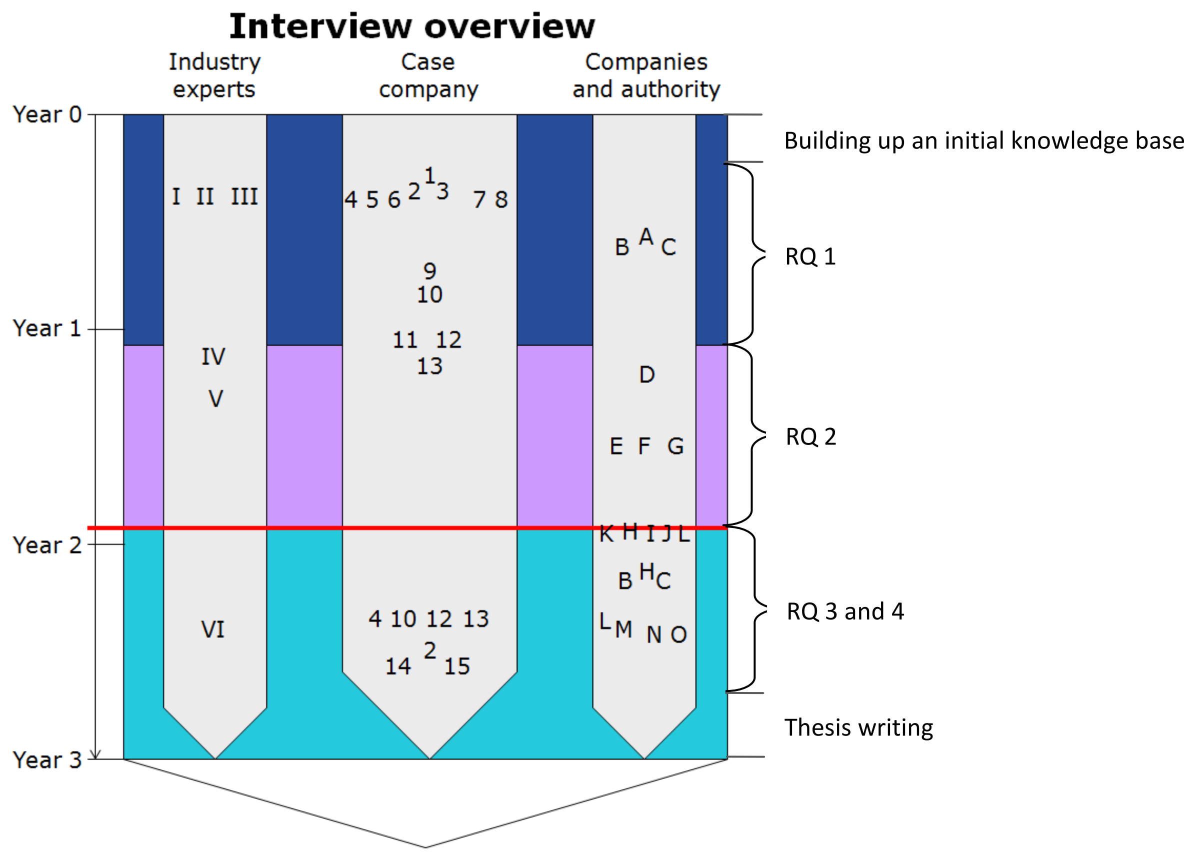

Figure 4: Overview of the interviews conducted in this PhD project in relation to the research questions and the time elapsed

Legend:

Focus to provide foundation to answer RQ1: This period of time is indicated by the dark blue color (~year 0 to year1):

- What does the requirements management process look like in Danish construction companies?
- What is the "typical" requirements management process?
- What kinds of scenarios are there concerning requirements management?
- What are reasons for not or only partly using formal requirements management?
- What are the obstacles?

Focus to provide foundation to answer RQ2: This period of time is indicated by the purple color (~year 1 to year 2):

- What could a structure that can contain all requirements of the case project look like?
- What could a requirements management framework look like?

Focus to provide foundation to answer RQ3 and RQ4: This period of time is indicated by the turquoise color (~year 2 to year 3):

- How can the developed RMF be implemented and used on the case project?
- Efficiency of the RMF
- Generalizability of the RMF
- And finally, the validation of the RMF!

Red line:

- Introduction of the RMF (~year 2)

The different questionnaires used for the interviews can be found in Appendices 1 to 3. Please note that – as shown in Figure 4 – sometimes the same people were interviewed twice. In those cases the second interview was held for validating (face validity) the RMF.

Critique: Even though the questionnaires used for the interviews were in English, the speaking parts of the interviews were held in four languages: Danish, English, German, and one interviewee even answered in Swedish while I was speaking Danish to him. Albeit the order of the questions was the same, and pictures and examples were used using different languages could in theory have led to some details not being caught; therefore, the minutes of meetings were used to ensure that the correct meaning was conveyed. Five of the interviews were conducted by phone. The rest of the interviews were held face-to-face. This could have been another factor contributing to not receiving 100% of the message.

2.2.3 LITERATURE STUDY

In order to create the RMF, literature from many areas had to be studied. Here are the main areas:

- Requirements management
- Requirements management in construction
- Systems engineering
- Project management
- Product lifecycle management
- Technical change management
- Construction
- Framework models
- Product platforms
- Product variants and product families
- Modularization
- Mass customization
- Manufacturing strategies
- Product architecture and interfaces
- Product design

- Product development
- Validation
- Action research
- Case study
- Qualitative research

There was an extensive literature study at the beginning of this research project to get a solid base to stand on. After that, literature studies were carried out for each of the articles and for the thesis.

2.2.4 SYNOPSIS OF ARTICLES

Seven articles were produced during this PhD project. Three of them were for conferences and four were targeted at journals. Figure 5 shows a synopsis of those articles whereas Table 1 shows an overview of the content of the individual articles.

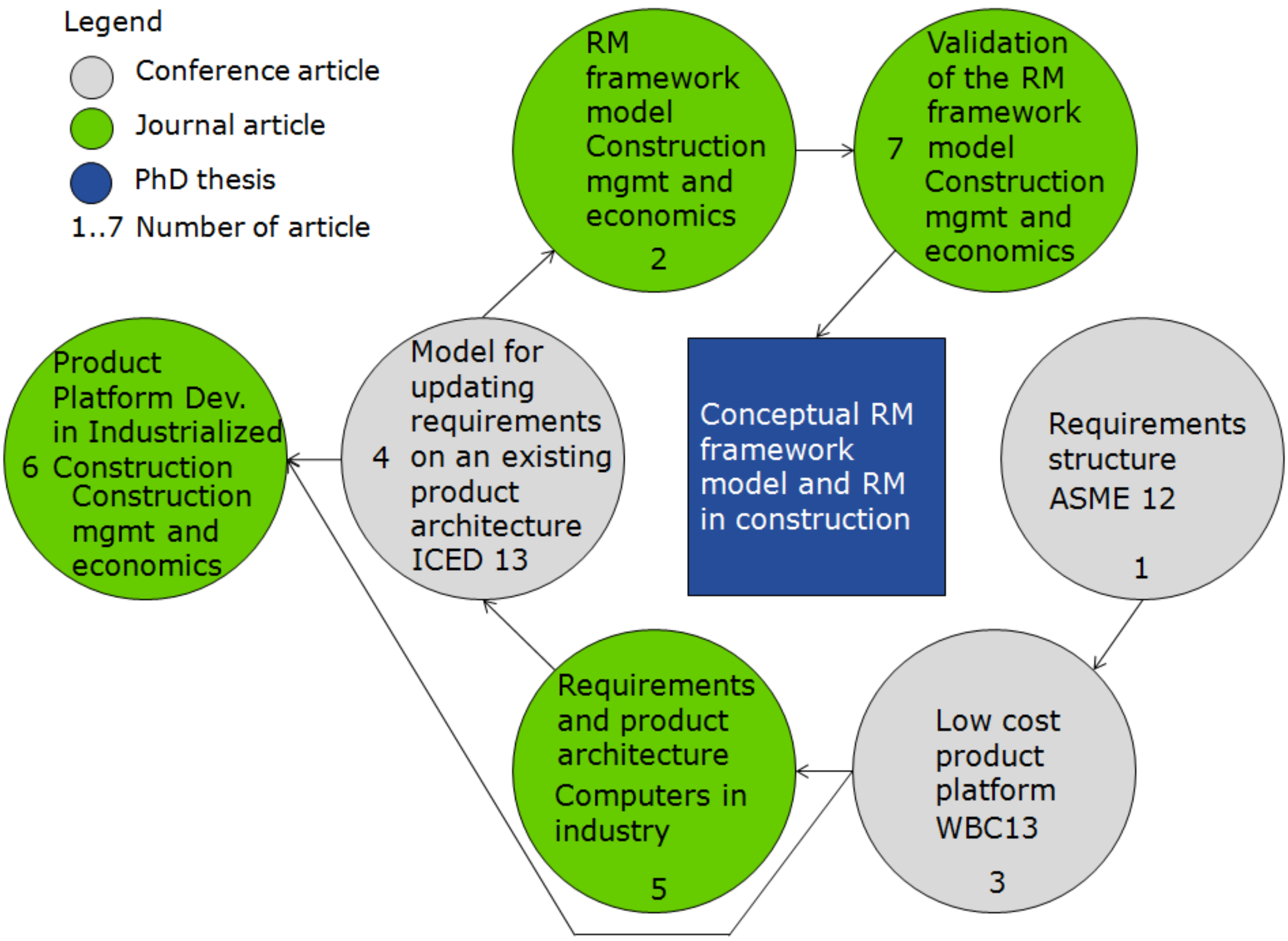

Figure 5: Synopsis of the articles produced during this PhD project

Table 1: Overview of the content of the individual articles

		Scenario												
		Product architecture	**Product development**	**Product platform development**	**Construction project(s)**		**New product development**	**Product upgrade**		**Requirements management in general**	**Requirements management in construction**		**Requirements management framework**	**Validation**
Described in	**Article 1** ASME 12 – Requirements structure	X	X	X	X		X				X			
	Article 3 CIB 13 – Low cost product platform			X	X						X			
	Article 5 Requirements and product architecture	X												
	Article 4 ICED 13 – Updating requirements	X	X				X	X		X				
	Article 6 Product platform development in industrialized construction	X		X						X				
	Article 2 RM framework				X								X	X
	Article 7 Validation of the RM framework				X									X
	PhD thesis									X	X		X	X

2.2.5 MAPPING OF ARTICLES VS RESOURCE QUESTIONS

The four research questions of this PhD project were scrutinized in seven articles. Not every article covers each research question. Therefore, Table 2 shows a mapping.

Table 2: Mapping of articles vs. research questions

	RQ1 **What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?**	**RQ2** **How should a requirements management framework be built up in order to counteract the requirements management related challenges that construction companies face?**	**RQ3** **How can the developed requirements management framework be implemented and used on the case project?**	**RQ4** **Can the effectiveness and generalizability of the requirements management framework be demonstrated and how can they be validated?**
Article 1 – Requirements structure	X	(X)		
Article 2 – Requirements management framework	X	X	X	X
Article 3 – Low-cost platform of the case company	X	(X)		
Article 4 – New / updating requirements on an existing product architecture	X	(X)		
Article 5 – Product architecture	(X)	(X)		
Article 6 – Product platform development in industrialized construction	X	(X)		
Article 7 – Validation of the req. mgmt. framework	(X)	X	X	X

X = The research question is directly covered by the article

(X) = The research question is indirectly covered or not covered in detail by the article

2.3 VALIDATION OF RESULTS

The validation of scientific results derived from qualitative research in general and action research in particular, as described by Checkland and Holwell (1998), sometimes poses a problem for the researcher. This is due to the fact that it can be difficult for the researcher to prove validity, reliability, effectiveness, and generalizability of the research. Furthermore, when using action research, the researcher has to be careful not to be a consultant masquerading as a researcher but a real researcher. In order to avoid those pitfalls Coughlan and Coghlan (2002) and Mishler (1990) have been consulted.

The fourth research question targets the above mentioned difficulties. Therefore Articles 2 and 7 describe the validation of the RMF which comprises a big part of this research.

As shown in Figure 6, the whole process of making and validating the RMF can be divided into three phases: The first phase, indicated by a light pink color, is called the "Gathering of knowledge that is required to develop RMF". This phase contains the general gathering of knowledge, structured and unstructured interviews, as well as analyses. The phase is concluded with a recommendation.

The second phase, indicated by a light blue color, comprises the development of the RMF.

Whereas the third phase, "Testing and validating the RM framework", indicated by the green and yellow colors, consists of the steps that were used for validating the developed RMF, a recommendation to apply the framework to further building projects (yellow color), and an update of the framework. Phase three concludes with obtained new knowledge and contribution to theory.

The following four steps were used for *validating* the developed RMF:

- "Theoretical validation of the framework",
- "Expert interviews / revisiting interviews",
- "Interviews abroad", and the
- "Test house"

Rykiel (1996), Mishler (1990), McCarl (1984), and Jabareen (2009) were the strongest contributors of theory about the validation of qualitative research. Mishler's way of looking at validation (see section 5.6) especially had a strong impact on my own perspective on how good validation should be carried out.

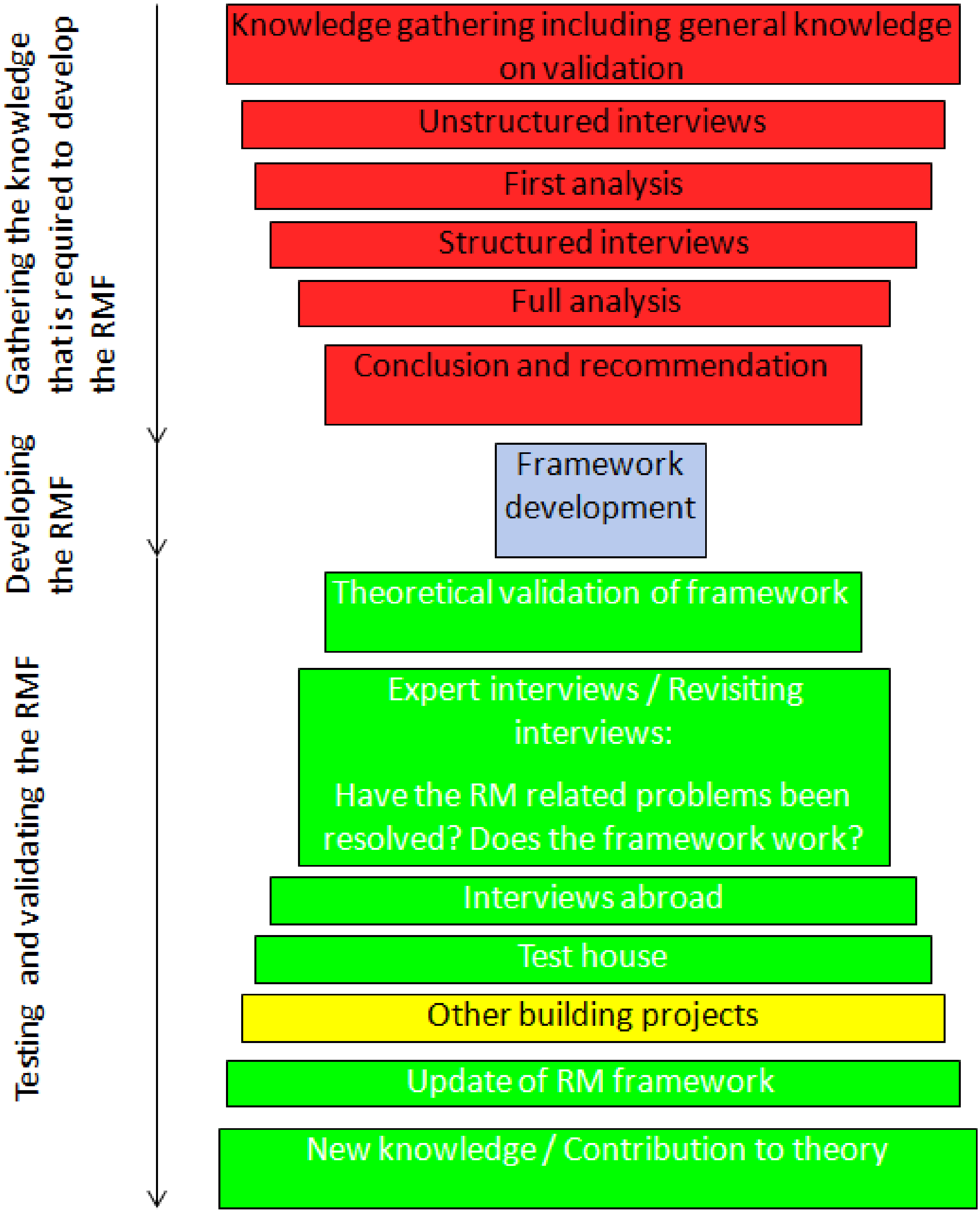

Figure 6: Steps for making and validating the RMF (Figure taken from Wörösch and Mortensen 2014, p. 5)

3 THEORETICAL BASIS

In the previous section the applied research approach was described. In this section it is recognized that research on requirements management in construction requires consideration and inclusion of several theories and domains in the underlying theoretical basis in order to be able to cover the whole research topic. Hence the purpose of this section is to (1) provide an overview of relevant theories and domains associated with the research topic and (2) show and structure the contextual (and product) differences of the sector of software development and the construction industry.

3.1 DIFFERENT APPLICABLE THEORY AREAS AND DOMAINS

Four theories, two domains, one framework, and one engineering discipline were identified as the main contributors to this research:

- Systems engineering (domain)
- Project management (domain)
- Requirements management (engineering discipline)
- Decision making theory (theory)
- Theory of technical systems (theory)
- Theory of dispositions (theory)
- Theory of domains (theory)
- Framework of Integrated product development (framework)

The relevance for this research of each of the above will be investigated in the following sub-sections. Please note that there is interplay between the theories, domains, framework, and engineering discipline that are the basis for this research. This interplay is not described.

Only the *main* contributors are described in this section. This does not mean that other theories and domains e.g. organizational theory, actor network theory, change management, and the like are not applicable to this research. But as those are considered secondary contributors they are not described here.

3.1.1 SYSTEMS ENGINEERING

Systems engineering is defined as "an interdisciplinary approach and means to enable the realization of successful *systems*. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: Operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" (INCOSE 2011, p. 6). A simpler, non-scientific explanation of systems engineering, that is closer to a practitioner's heart, can be found on Wikipedia (2013): “Systems engineering is an interdisciplinary field of engineering that focuses on how to design and manage complex engineering projects over their life cycles”.

The domain of systems engineering emerged as an effective way to manage complexity and change. It was primarily applied to large and complex projects. According to Aslaksen (2005) systems engineering has traditionally been used in the aerospace and defence industry but is applied today to other industries such as the manufacturing, service, and process industries as well, as the application of systems engineering has proven to have a positive impact on cost and schedule when developing a system: “The time from prototype to significant market penetration has dropped by more than a factor of four in the past 50 years (INCOSE 2011, p. 15)”. Aslaksen (2005) states that the application of formal systems engineering to construction is at its very beginning. In his later article (2006) he also states that systems engineering equally applies to all industry sectors.

INCOSE has recognized the need for systems engineering in construction by issuing a *guide for the application of systems engineering in construction* (INCOSE 2012). So far this guide only covers large infrastructure projects. What is interesting about this guide is the fact that it breaks (as by systems engineering experts strongly advocated) with the principle of making a prototype before building the actual product – as the prototype of a large infrastructure / building is the actual infrastructure / building. INCOSE´s mid-term goal is cooperation with the American Society of Civil Engineers (ASCE 2013). Once this cooperation is established other areas of the construction industry will be able to benefit from systems engineering as well.

With regard to systems engineering, this research project can be seen as a vanguard as it already today applies elements of systems engineering to construction. This was done by applying the V-model (which is a graphical representation of the systems development lifecycle showing the main steps and the corresponding validation) and formal requirements management processes as described in the systems engineering handbook (INCOSE 2011, p. 27) to the case project. The application of systems engineering was done with one modification, though: *Systems thinking* was adopted towards *projects thinking*.

The building blocks “Life cycle approach” and “Test, verification, and validation” of the RMF are based on the systems engineering handbook, so is its iterative approach (INCOSE 2011).

Contribution to this domain: The knowledge and data gathered when applying elements of systems engineering to the construction industry can be used by, for example, the INCOSE infrastructure working group (INCOSE 2011) to drive the application of systems engineering in this sector. It is expected that the construction industry thereby achieves some of the benefits that usually are connected to systems engineering (Frederick and Sauser 2007).

General experts of systems engineering will benefit from this contribution as well as it gives them an indication of the practical boundaries of systems engineering.

3.1.2 PROJECT MANAGEMENT

The domain of project management is defined as “the application of knowledge, skills, tools, and techniques to project activities to meet the *project requirements”* (PMBOK 2013). Project management can be divided into ten knowledge areas:

- Project integration management
- Project scope management (This knowledge area contains formal requirements management and should, in my opinion, be the first knowledge area that is defined in a project. Defining the other knowledge areas first makes sense after that)
- Project time management
- Project cost management
- Project quality management
- Project human resource management
- Project communications management
- Project risk management
- Project procurement management (covering contracts that contain requirements)
- Stakeholder management

and five process groups:

- Initiating process group
- Planning process group
- Executing process group
- Monitoring and controlling process group
- Closing process group

The knowledge areas are integrated with each other, i.e. when changes happen in one knowledge area it will impact some, if not all, of the other knowledge areas. This is governed by the knowledge area project integration management.

Example: A new requirement is coming into a project saying that developed high performance concrete material has to withstand fire at a temperature of 1000 degrees Celsius for a duration of one hour instead of ten minutes. Changing the project scope by adding this new requirement will impact the time management of the project as tests have to be planned and executed. Those tests cost money, ergo they will it have an impact on the project cost management as well. What happens if those tests fail? This will be handled by the project risk management and so on. This example is merely a taste of the complexity that had to be handled in the case project.

Kerzner (2003, p. 57) offers a different definition of project management: "Project management may ... be defined as the process of achieving project objectives through the traditional organizational structure and over the specialities of the individuals concerned".

Kerzner (2003) and the PMBOK (2013, p. 3) seem to be in agreement when it comes to the definition of a project. They both see it as: "A project is a temporary endeavour undertaken to create a unique product, service, or result". The PMI standard (PMBOK 2013) was chosen as the main source for this sub-section as it is known by most project managers of the world.

I am aware of the fact that not only general literature on project management but also literature on project management that is specifically targeted at the construction industry is available: In their book "Modern Construction Management" Harris and McCaffer (2012) cover many, but not all, core aspects of project management. Their focus lies in the areas of project management that are especially relevant in construction.

Barrie and Paulson (1978) offer an alternative to Harris and McCaffer (2012) in "Professional Construction Management". They also focus on project management in construction. What makes their book relevant for this research is their section on "requirements of the professional construction manager" (pp. 44).

Already the title of this thesis indicates that project management is relevant to this research as it contains words like "multi-*projects*" and "requirements management". Furthermore, project management was applied to run the case project. Apart from that the building blocks "Organisation", "Prioritisation and documentation of requirements", and "Project execution and monitoring and controlling of requirements" of the RMF were developed based on a project management specification (PMBOK 2013).

Contribution to this domain: Project management, with its main focus on project scope management, was applied to building projects and development projects in the construction industry. The knowledge and data gathered when doing so can be used to further improve the PMI standard (PMBOK) to better fit the needs of the construction industry. This will potentially lead to better project management and thereby fewer delays and budget overruns, as well as increased quality in this industry.

3.1.3 REQUIREMENTS MANAGEMENT

This sub-section is relevant as this thesis and research are about *requirements management* in construction. Therefore, requirements management should be explained: Requirements management is not a theory, domain, or framework but an engineering discipline. I personally see requirements management as a subset of systems engineering but I know that others do not. They might see it as part of project scope management (in chapter 5, pp 105 of the PMBOK (2013) the relation between project scope management and requirements management is described) or something else and therefore not agree with my perception.

The following two paragraphs are directly taken from Article 4 (Bonev et al. 2013, p. 3-4). The references in those paragraphs can be found in the reference list of Article 4.

"*At the heart of any engineering discipline is the interplay between problem and solution domains (Chen et al, 2013). A requirement specifies what the product must do or defines a quality that the product must have (Robertson and Robertson, 2013). Compelling economic arguments justify why an early understanding of stakeholder' requirements lead to systems that better satisfy their expectations (Nuseibeh, 2001). Requirements Management (RM) proposes methods to cope with the requirements at the early phases of the development life cycle. It presents concepts of identifying, collecting, and allocating "system functions, attributes, interfaces, and verification methods that a system must meet including customer, derived (internal), and specialty engineering needs" (Stevens and Martin, 1995, p.11). On the one hand RM consists of soft processes focusing more on people than products. This characterizes at the requirement elicitation process where requirements are discovered and the main objectives are about understanding stakeholders and discovering needs. When the problem domain is sufficiently well defined, on the other hand harder and more definite modeling techniques can take over (Alexander and Beus-Dukic, 2009). Since detailed descriptions for the requirement specification are typically created in various text based documents of considerable length, it can be difficult to get a sufficient overview of the requirements.*

In RM requirements are typically grouped and graded according to their nature, e.g. implied or derived, and the impact the stakeholders have on them (DeFoe, 1993). Investigations on RM challenges have been reported repeatedly over the past years (Juristo et al., 2002). Requirements presentation, as well as incomplete and changing requirements and specifications are thereby seen as a major obstacle that needs to be overcome (Weber and Weisbrod, 2003). The process of moving between the problem world and the solution world is furthermore still not well recognized. Typically the effectiveness of a solution is determined with respect to a defined problem, however, the nature of the problem and its scope could depend on what solutions already exist or what solutions are plausible and cost-effective (Chen et al., 2013). Recent models suggest that instead of doing RM only at the early phases, requirements definition and design are interactive activities, handled simultaneously through the development life cycle (Nuseibeh, 2001). RM therefore concerns much more than a list of "shall statements". Instead in modern approaches RM issues are engineered, involving tools, modeling, database design, customization with scripts, training, and data handling (Alexander and Beus-Dukic, 2009)".

As for requirements management in construction, the "traditional approach" for building up a project and dividing responsibility is often covered by national standards. Having such a standard influences many of the processes that are used in construction. Requirements management is considered one of those processes.

The umbrella-standard that is valid for Denmark is called ABR-89 (1989). In this set of rules the construction project is divided into five phases and some requirements are stated for each of those phases. But: (1) many different requirements that are not covered by ABR-89 do exist in a building project. (2) this umbrella-standard does not tell construction companies how to actually manage their requirements and (3) issuing a standard does not mean that construction companies are living up to it.

A consequence of ABR-89 is that not all stakeholders can change requirements in any phase of a building project. The exception to that rule is the customer. But, as a penalty for initiating a change, the customer has then to pay for the changes he or she wants. This can get expensive in the later phases of building projects.

When analyzing the "traditional approach construction project" it becomes clear that not all stakeholders have requirements for all phases. Typically, a customer has requirements up to the design phase and is not necessarily interested in the technical requirements and requirements coming from laws, rules and regulations, and standards of the subsequent phases. An interesting observation here is that customers could be much better integrated into the formalized process of managing requirements. This is of utmost importance for POL-1. One of the interviewed companies operating in POL-1 even wants to use the RMF for better explaining the building process to their customers and at the same time integrating the customers much more.

Formal requirements management was used on the case project to manage *all* encountered requirements, i.e. not only product related requirements but also requirements related to sales, market, business, authorities, ... In that way the main goals were first broken down to sub-goals and then to requirements. As the main goals often are linked to a vision the requirements should – as a sum – reflect that vision.

Contribution to this domain: This research has provided a structure for managing requirements that can inspire other construction companies, a RMF, and The product requirements development model. Potentially this research has contributed to moving an entire field of business. The effect of that will surface within the next few years.

3.1.4 DECISION MAKING THEORY

Decision theory "focuses on how we use our freedom. In the situations treated by decision theorists, there are options to choose between, and we choose in a non-random way. Our choices, in these situations, are goal-directed activities. Hence, decision theory is concerned with *goal-directed behaviour in the presence of options"* (Hansson 1994, p. 6).

As Hansson (1994, p. 6) explains, we do not decide continuously but "in the history of almost any activity, there are periods in which most of the decision-making is made, and other periods in which most of the implementation takes place".

Decision theory looks both into how decisions should be made (normative) in order to be rational, and into how decisions are actually made (descriptive). Decision theory supplies methods for e.g. a business executive to maximize profits (economic rule of maximization), but does not address the question of whether the executive should do business in the first place.

In 1793 the philosopher Condorcet divided the decision process into three stages (taken from Hansson 1994, p. 9):

1) Examination of the different aspects of an issue and the consequences of different ways of making the decision (done by individuals)
2) Discussion to clarify "the question" and combination of the different individual's opinions (majority of individuals rules)
3) Choice between alternatives

Later (1962, p. 9) Brim et al. refined the decision process:

1) Identification of the problem
2) Obtaining necessary information
3) Production of possible solutions
4) Evaluation of such solutions
5) Selection of a strategy for performance

Sometimes, it is necessary to take decisions under uncertainty. Once a decision has been taken it can turn out to be unstable.

Cyert and March (1963) published the book "A behavioural theory of the firm". In this book they focus among other things on decision-making in organizations under uncertainty. Cyert and March are considered key researchers in decision theory.

In 2005 Robert J. Aumann and Thomas C. Schelling were jointly awarded the Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel for their research in conflict and cooperation through the lens of game theory. For that they used *interactive decision theory* looking into why some groups of individuals, organizations and countries do succeed in promoting cooperation while others suffer from conflict (Nobelprize 2014).

In this research the decision theory was applied a number of times: The RMF requires the project manager to take plenty of decisions, e.g. when requirements are contradictory or what processes to apply to the project when several similar processes are available. Article 4 described a model for updating requirements on an already existing product architecture that results in numeric values. Based on those values the project manager and designer have to take the decision on whether a design change should be implemented or rejected.

On a high level, the decision theory was applied to the case project when not enough resources were available to develop three product platforms at the same time (which product platform to put on hold) and when building projects were prioritized over each other.

3.1.5 THEORY OF TECHNICAL SYSTEMS

In their theory of technical systems (TTS) Hubka and Eder (1988) describe a framework for understanding products and other artefacts as technical systems. The theory describes how a transformation of an operand takes place on the basis of a relation between the technical system, the human system, the information system, and the management and goal system, all of which are affected by the environment. The operand is the object of transformation, i.e. the object changes state during the transformation. Figure 7 depicts a model of Hubka's and Eder's transformation system.

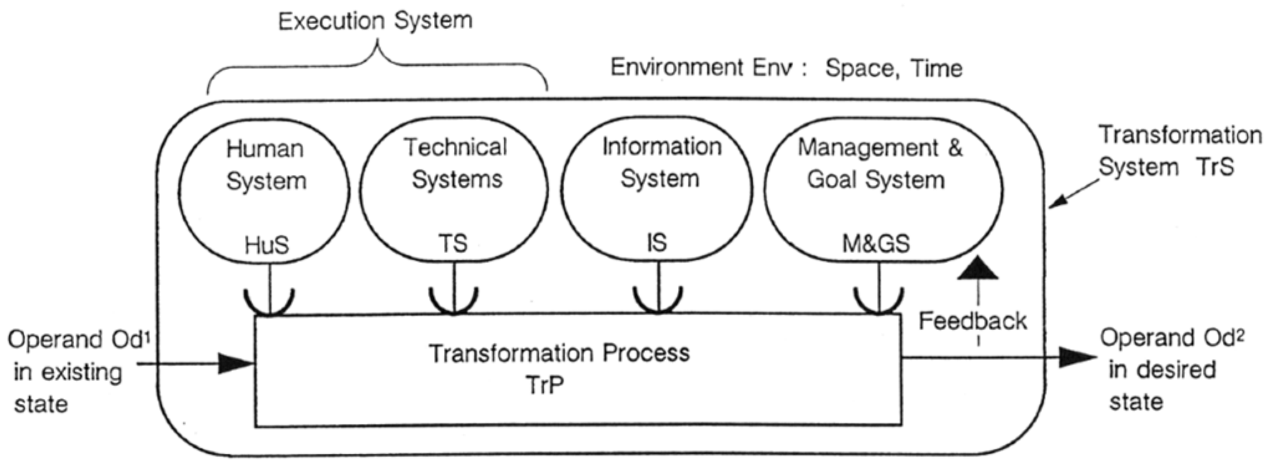

Figure 7: Model of the transformation system (Hubka and Eder 1988, p. 24)

Two kinds of processes are found in a transformation system: (1) a technical process which transforms the operand, and (2) an action process delivering an effect to the technical process.

In order to show the boundaries of the terms they use for describing the TTS more clearly, Hubka and Eder show a hierarchy of systems according to their origin. This hierarchy relates technical systems to other types of systems and can be seen in Figure 8. A system consists of elements and can therefore be broken down. A system can also be an element of a larger system.

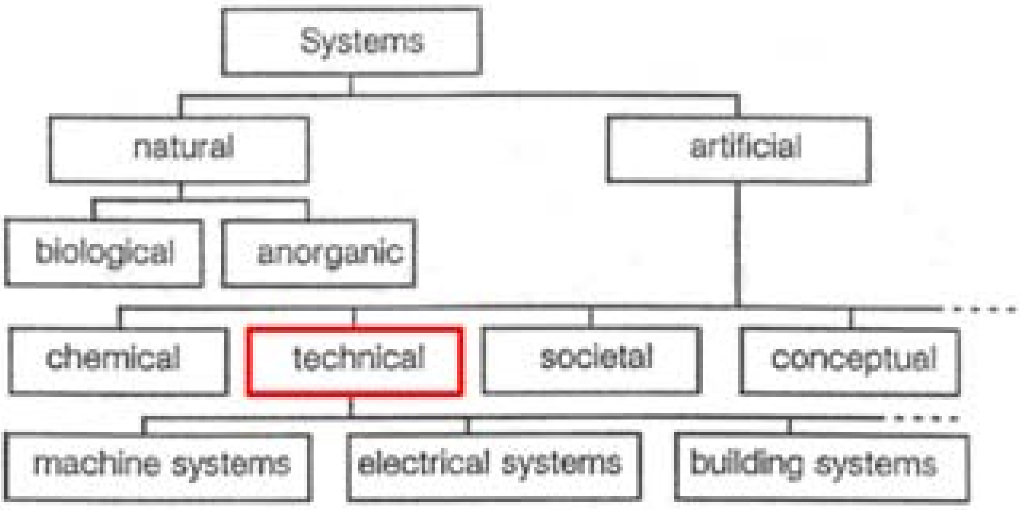

Figure 8: Hierarchy of systems (Hubka and Eder 1988, p. 8)

The TTS is important to this research as it provides a means for understanding and describing a technical system.

Pedersen (2010, p. 59) argues that "a product platform can be perceived as a set of technical systems that can be altered and / or combined into instantiations (configurations) of single products". As this research project and the case project attached to it deal with product platforms the TTS is highly relevant here.

The TTS was also applied when analyzing the production of sandwich panels in the case project.

Example: Raw material came into the factory (operand 1) and was transformed into sandwich panels (operand 2). Considering the production as a system made analyzing it easier and helped with understanding the connection to its surrounding systems.

3.1.6 THEORY OF DISPOSITIONS

The concept of dispositions was explained by Andreasen and Olesen in 1990. Later (1992) Olesen expanded the concept of dispositions into the theory of dispositions.

"The theory of dispositions treats relationships between parameters of a product and the parameters of the systems which are realizing the product and which the product meets during its life. When the theory is used during design the designer tries to foresee parameter relationships and choose the parameters of the product which optimize the conditions during production and product life" Olesen (1992, abstract).

Olesen (1992, p. 53) defines a disposition as: “...the part of a decision taken within one functional area that affects the type, content, efficiency or progress of activities within other functional units”. Andreasen (2007) explains a functional area as a ‘function unit’ in a company or as an activity in the life of the product.

Welsh and Dixon (1991, p. 61) found out that: “Conceptual design is the driving factor in determining product quality and time to market, and *it is estimated that 60% of all life cycle costs are fixed during conceptual design*. Downstream processes such as detailed design, manufacture, and inspection cannot make up for poorly developed conceptual design”.

According to Olesen (1992), dispositions are measured in terms of their effect on the universal virtues during development. Therefore a score model can be set up. Using the model will lead to estimated costs. Those have to be compared to actual costs. The model is shown in Figure 9:

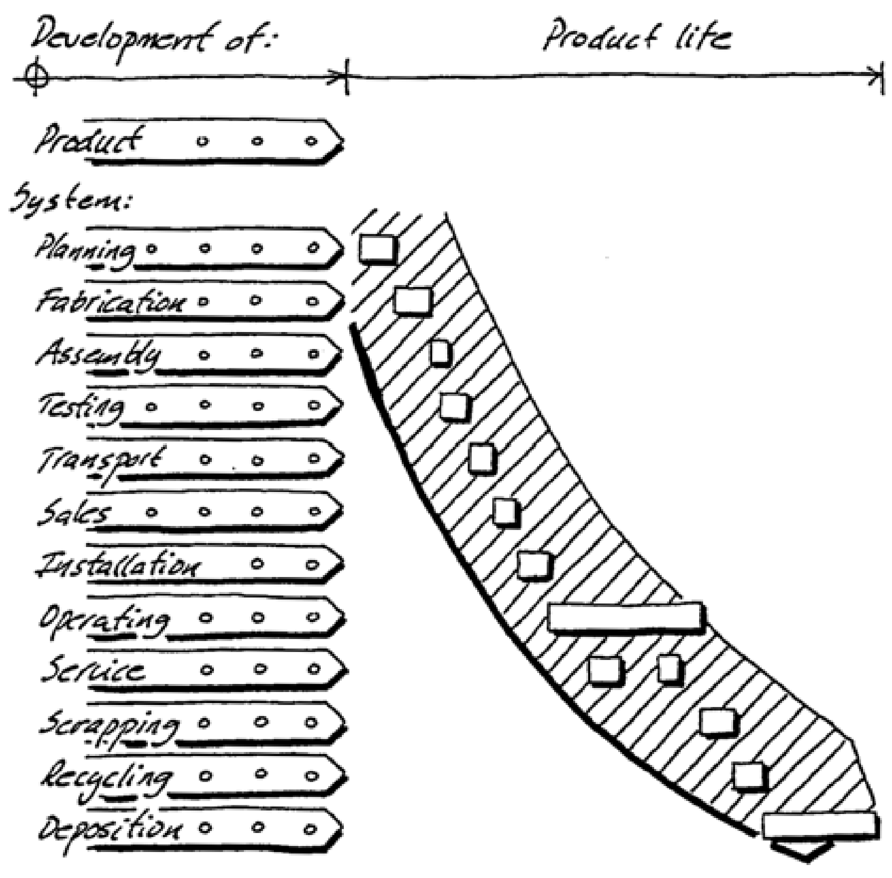

Figure 9: “A score model which gives an overall view of all systems which dispositions affect when a product is developed” (Olesen 1992, p. 58)

Even though Olesen tried out his theory on mechanical, hardware, and software products the principle of it was expected to work for design in construction as well. In the case project of this PhD the theory of dispositions was used when designing new products (walls, buildings...) and special emphasis was put on the financial impact of the taken design decisions on later stages of the product life cycle, for example transportation and assembly cost. The awareness of the consequences of dispositions made in one domain affecting other domains has saved the case company a considerable amount of money.

In order to get maximum benefit of Olesen's score model, staff of the case project designed the total product life cycle before designing the product, as recommended by Kimura & Suzuki (1996).

3.1.7 THEORY OF DOMAINS

"Domain theory is a systems approach for the analysis and synthesis of products. Its basic idea is to view a product as systems of activities, organs and parts and to define structure, elements, behaviour and function in these domains. The theory is a basis for a long line of research contributions and industrial applications especially for the DFX (Design For X) areas and for product modeling. The theory therefore contains a rich ontology of interrelated concepts (Chakrabarti and Blessing 2014, chapter 2, page number still unknown)".

The theory of domains was first published by Andreasen (1980) and was later modified to only contain three domains. The term *domain* refers here to a specific viewpoint and not to an engineering discipline.

According to the Theory of Domains, artefacts may be seen in three different domains:

- The activity domain: How a product is used. The *transformation process,* developed by Hubka and Eder (1988), shown in Figure 7 is the same as a technical activity in the theory of domains
- The organ domain: How the product functions. An organ is here defined as: "... a function element (or 'means') of a product, displaying a mode of action and a behaviour, which realise its function and carry its properties (Chakrabarti and Blessing 2014, page number still unknown)"
- The part domain: How the product is built up. A part is here defined as: "... an elementary material element of a part system. Parts are building elements of an organ, realising the organ's mode of action by the parts' physical states and interactions (Chakrabarti and Blessing 2014, page number still unknown)"

Based upon the domain theory, Mortensen (1999) proposed design languages for organs and parts (product modeling). Furthermore, Mortensen (1999) states that the main reason for considering designs as organs is that functionality can be explained, which is not the case when individual machine parts are modeled.

Figure 10 shows the three domains in which a product can be viewed.

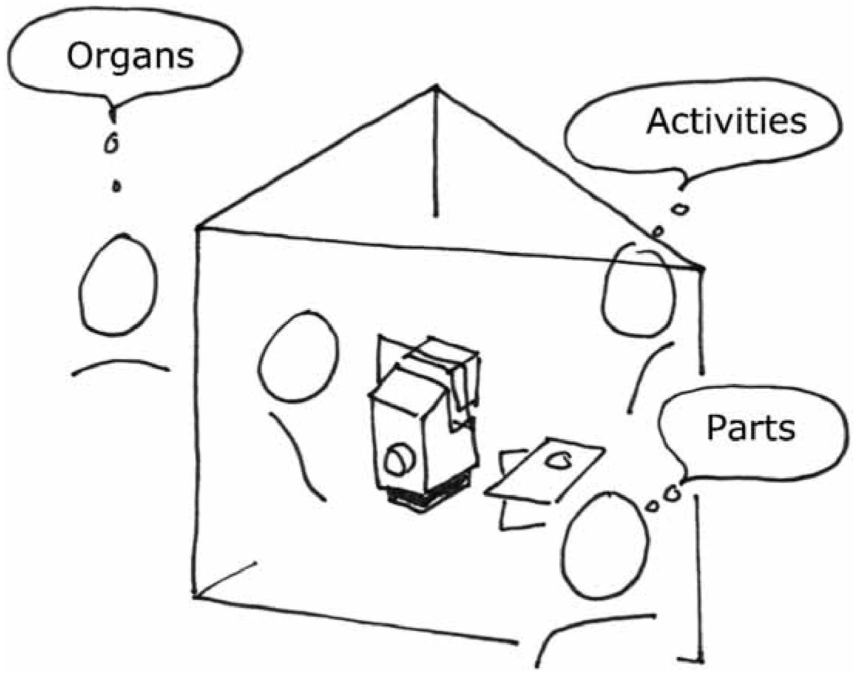

Figure 10: Three domains in which a product can be viewed, from Andreasen (2011, p. 15)

The theory of domains is an improvement of the TTS. The theory of domains seems to be the most up to date way of describing a technical system. The theory of domains is one way of describing a product's functionality and how a user can apply that product. Furthermore, it forms a basis for identification of standard designs that are similar, which can be used as a basis for re-use of design and parts as well as for exploiting synergies; for example, assigning the same resources to similar design activities. Harlou (2006) believes that the coherence between the domains enables reasoning from purpose of the product to the physical realisation of the product. He also deems that such coherence for a product family will ease decision making about the necessary variety within a product family.

On the case project the theory of domains was used for making the activity, organ, and parts view of the products (different types of buildings). Once those views were available they were used to re-use designs and thereby requirements between building types. Those views were also used to simulate what happens to an existing product architecture when new requirements are introduced.

3.1.8 INTEGRATED PRODUCT DEVELOPMENT

The framework of integrated product development as published by Andreasen and Hein (1987) is part of the overall strategic process of product planning. It describes the process as parallel and coordinated activities in the area of market, product and production.

The framework of integrated product development has a number of strengths. The ones I consider as most important are listed below:

- It addresses the development process at project level and relates it to the company level
- It considers the importance of management and supervision of both company and product goals in product development
- It uses project and product specifications for documenting goals, criteria, and requirements
- It describes the fundamental characteristics of the design process
- It acknowledges the importance of concurrent engineering

Figure 11 shows a part of the integrated product development framework.

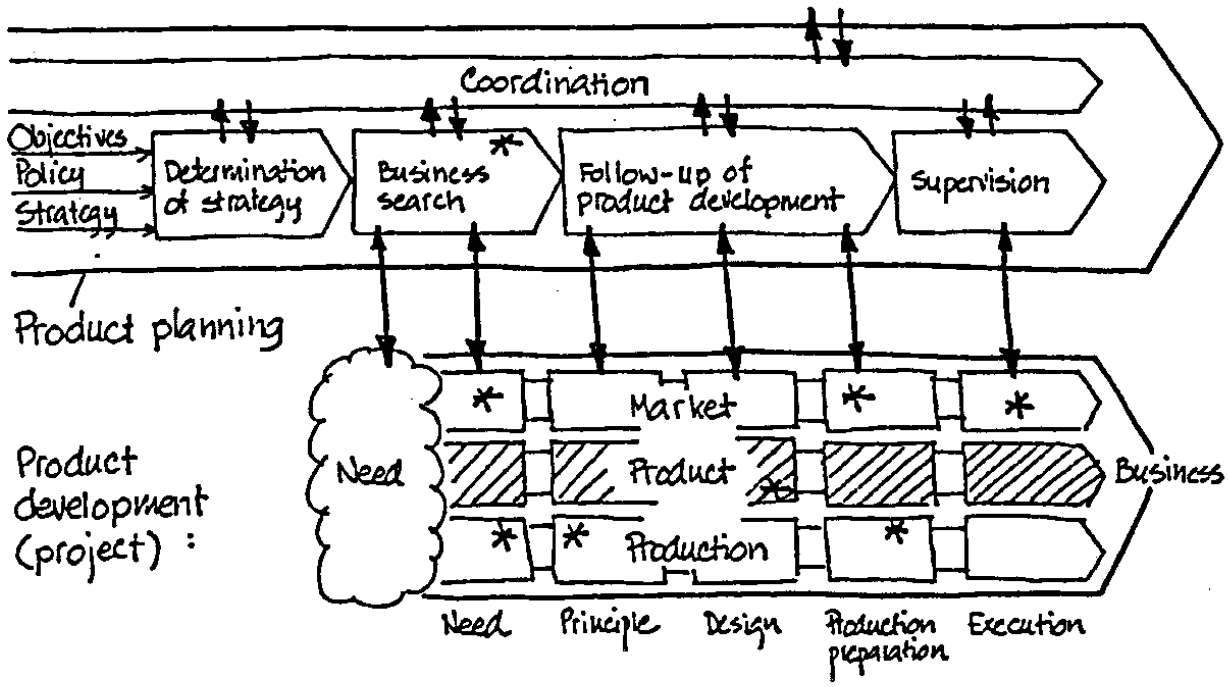

Figure 11: Part of the integrated product development framework (Andreasen and Hein 2000. Figure 11 has been taken from Tan (2000, p. 65) where it is part of a figure showing four patterns of design in product development)

A lot of innovation was done on the case project. This resulted in the design and development of several new products. The framework of integrated product development was used as a guiding high level process when developing new products. As the case project was under a tight time schedule many activities were carried out in parallel. The framework of integrated product development supports working under such conditions.

3.2 COMPARING REQUIREMENTS MANAGEMENT IN THE CONSTRUCTION AND THE SOFTWARE SECTOR

This sub-section was added as I see it as an important part of the theoretical base of this research. Especially during discussions with experts in systems engineering I often was asked the question: “Why don’t you apply systems engineering such as that used in the software sector?” When I then explained that this cannot be done due to contextual differences that need to be considered the next question was: “Are there really so many major differences that it matters considering them?” During those discussions it occurred to me that these experts in systems engineering do not consider the building industry as complex from a technical and systems point of view. Experience has taught me that herein lies a trap. Sub-section 3.2 was written in the light of those discussions.

When it comes to formal requirements management the sector of software development seems to be ahead of any other sector (Fernie et al. 2003, Krönert 2010). This can be seen by the sheer number of books and articles published on different topics related to requirements management in software development but also by the number of show cases and models that are available when using university libraries or Google (2013). Very often those models are well integrated with other approaches and models and also compatible with a whole series of standards and methods (ISO, CMMI, ITIL, PMI, PRINCE2, LEAN, Six Sigma, Agile and others). Links to those standards can be found in the reference list.

Formal requirements management is used in many different sectors (Rosenburg 2001, Fernie et al. 2003) and when looking at the economic value of its projects the construction industry would definitely be expected to be one of them. But as researched by Fernie et al. (2003) and confirmed by Girmscheid (2010a) as well as Yu and Shen (2013) requirements management has not had its breakthrough in the construction industry, yet. That is why Girmscheid (2010a and 2010b) created a base for requirements management in the construction industry in his “Anforderungs-Engineering-Prozessmodell (English: Requirements Engineering Process Model)” (AEP) and Yu and Shen (2013) are pin-pointing the need for a requirements management framework in the construction industry.

I am aware of the advice of Fernie et al. (2003, p. 364) that before mapping requirements management from one industry to another one has to understand the contextual differences (and product differences) of the sectors in question since sectors can be very different from each other. They also state that “There is a danger that construction researchers continue to search for instrumental improvement techniques from other sectors *in isolation from a grounded understanding of equivalent practices in construction*.” In order to avoid that mistake an attempt to find the main contextual differences and the product differences between the software development sector and the construction industry was made in Tables 3a and 3b. The tables are based on own experience, interviews, and literature review:

Table 3a: Contextual differences between the construction industry and the sector of software development

	Software development sector	**Construction industry**
Approach to systems design	Find errors as early as possible	Issues are fixed on the fly
Following a phase model	An attempt is made to work in one phase of the project at a time	Often work is done in several phases at the same time
Time and cost management	Have necessary detailed plans in place	Often no overall detailed plan exists. 17.5 % of the building projects in Denmark have a schedule overrun (Byggeevaluering - nyheder 2013 and Byggeevaluering - analyse 2009). Not having a detailed plan is a main contributor to delays Note 1: Since there is no official statistics from the government on delayed building projects in Denmark, numbers from a professional organization were used here. Note 2: Those numbers only represent 2% of all building projects in Denmark but at the same time comprise the largest existing statistics on schedule overrun of construction projects in the country
Economical parameters	Typically medium to high profit margin	Low profit margin. Often as low as 1-3%
Introduction of new technology to the customer	Constantly	More conservative in nature. New technology has to be proven before it is applied to the bulk of customers
Approach to requirements management	Often professional requirements managers are being used	No total overview exists in one place. Rarely a dedicated person for requirements management is used on construction projects
	Requirements are locked as early as possible	Requirements are locked as late as possible. This is seen as an advantage
Change management	Responsible change manager pushing for early or no changes. Changes are seen as a disturbance	Changes frequently come at a late stage and often the project manager acts as a change manager. Changes are used to generate extra income
Customer / user involvement	Interviews of selected users or close cooperation with key customer	Interviews of selected users or close cooperation with key customer
Learning curve	Continuous learning, Lessons Learned applied at end of project	Low focus on learning curve and Lessons Learned. Fewer resources allocated for improvement
Agile development (Agile 2013)	Often used	Early adopters are currently looking at how Agile can be applied

Table 3b: Product differences between the construction industry and the sector of software development

	Software development sector	**Construction industry**
Life cycle and life expectation	Software lifetime expectation is often 8 years or less. Lifetime of systems can be prolonged by applying a SOA architecture (link in reference list)	Physical object – 100 years for brick houses and up to 200 years for concrete houses. The concrete standard (Dansk Standard 2002) requires 70 years of lifetime
Major renovation	SOA (link in reference list) facilitates replacing whole modules	So far rather expensive and taking a long time. Some vendors offer modular solutions
Maintenance / continuous improvement	Periodic software patches. Minor hardware replacement	On a continuous basis
Production	Very little pollution	Polluting factories, heavy CO_2 emission
Environmental considerations	Small for software itself	Toxic waste, recycling, extracting the building materials from the ground and transportation to the building site has a negative impact on the environment. Often regulated by law
Traceability of materials used and elements built	Configuration management and version control mechanisms are applied	Getting more important since it is required by law. But a lifetime expectancy of 70 – 200 years and people's attitude towards that (direct quote: "In 200 years I am dead, anyway") does not push for traceability
Transportation of the product	CD or download	Heavy transportation. Typically by truck or train
Assembly	During software and system builds	Built on-site or pre-fabricated at factory and assembled on-site
Testing	System tests and other tests are usually well defined. Often up to 30% of the total cost is used on testing and verification	Following standards. Doing test that is required by law. But typically no further testing or verification and validation is done

Although having highlighted differences in Tables 3a and 3b, when it comes to customer and user involvement there is a similarity. Also the attempt to introduce Agile development to the construction industry could, if successfully implemented, in the long run lead to further similarities between those two sectors.

Even though the above shown bulk of contextual and product differences between the two sectors differ a lot it is my conclusion that it is possible to successfully apply formal requirements management to the construction industry as long as the contextual differences of those rather dissimilar sectors are considered (so the experts in systems engineering were partly right but at the same time they underestimated the technical and systems complexity within the construction industry). Furthermore, it is my belief that appertaining key learning points can be taken from the software development sector as well.

Finally, I conclude that the construction industry should sooner rather than later try to learn from software development and start minimizing the following contextual differences: Errors should be found and requirements should be locked as early as possible. This requires a change of mind-set and the use of dedicated requirements managers. But if done successfully those changes will help the construction industry to overcome some of the previously mentioned challenges.

3.3 CONCLUSION OF THEORETICAL BASIS

Four theories, two domains, one framework, and one engineering discipline were identified and described as a pertinent base for doing research within requirements management in construction as they help in forming fundamental assumptions regarding research aim, research object, and research approach. Those were: Systems engineering, project management, requirements management, decision making theory, theory of technical systems, theory of dispositions, theory of domains, and integrated product development.

The theoretical base was brought to a close by comparing how requirements management is done in the sector of software development and in the construction industry to each other in order to avoid the trap of blindly mapping from one sector to another without having a deeper insight into fundamental differences and consequences hereof. This comparison is shown in Tables 3a and 3b and provides an essential understanding of the mindset and core concepts that were used for this research. After analyzing Tables 3a and 3b I arrive at the conclusions that (1) it is possible to successfully apply formal requirements management to the construction industry as long as the contextual differences are considered and (2) that the construction industry should learn from the software development sector.

4 PRACTICAL BASIS

The purpose of this section is to explain the practical foundation of this research, which consists of two parts: (1) The case company and (2) the interviews conducted at other companies within the field of construction, to the reader. I have chosen to call this section “Practical basis” instead of “Empirical basis”, which would have been more correct within the academic world, to be more appealing to managers who are working in the construction industry.

It is attempted to give the reader a picture of the case company, its history and markets, products and platforms, organization and stakeholders, value chain and order scenarios, in addition to some examples of recent innovation. The description of the case company is concluded by elucidating how requirements management was done on the case project and the “flow” of technical requirements that was encountered there.

The second part of the practical base provides a first glance at the interviewed companies by looking at the types of construction projects they engage in and the kinds of projects they run besides construction projects. This part of the practical base is closed by giving a high level introduction to the way requirements management is carried out at those companies.

After having read the theoretical (section 3) and practical (section 4) basis the reader should have a better understanding of the groundwork that this research is based upon.

Both the theoretical and practical base were used to gather input for developing the RMF, developing the RMF, applying the RMF to real world situations, and testing and validating the achieved results.

4.1 THE CASE PROJECT / COMPANY

Giving a description of the case company – connovate a/s – is necessary because this company is far from *the classical construction company*. It is extremely innovative and risk taking and requires therefore a more detailed description. But being aware of those risks it tries to mitigate them by involving experts – practitioners as well as academics – from different fields.

Being innovative and risk taking was experienced in the case of connovate in running: Product development, technology development, product platform development, and building projects – in parallel.

4.1.1 HISTORY AND MARKETS

connovate started as a development project in 2008 and was officially founded as a company in 2012. Figure 12 shows the timeline of the connovate development project up to the point of founding the company.

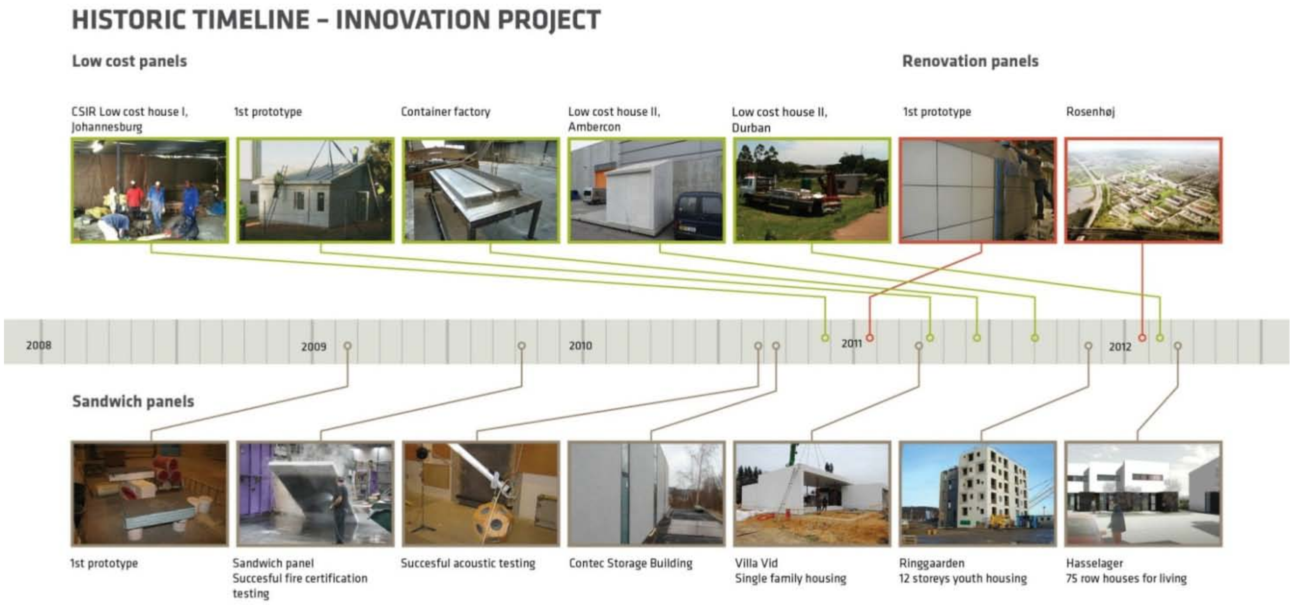

Figure 12: A historic timeline of connovate showing the results of the development project (connovate 2013)

connovate has its base in Denmark but is – via licensees – already active in South Africa. The strategy is to be a global player. Figure 13 shows the global strategy for the case company's market presence.

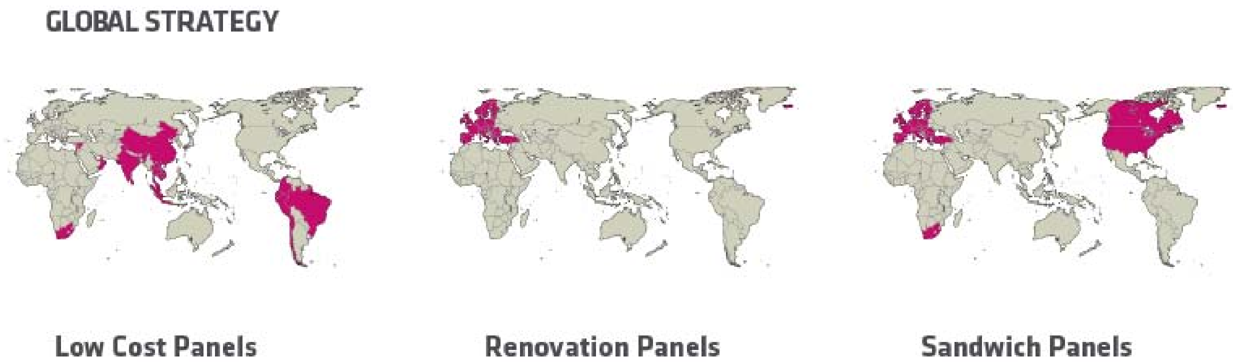

Figure 13: The global market strategy of connovate (connovate 2013)

The aim is to be present on multiple continents with trademarks, patents, and domains to create a strong alternative to existing building systems.

4.1.2 PLATFORMS AND PRODUCTS

connovate has three product platforms (Figure 14) that are based on High Performance Concrete (HPC) sandwich elements:

- A product platform of load and non-load carrying sandwich elements for the high end Western market (please note that this high end product platform currently also covers the mid-range market) used to make sustainable housing
- An insulation panel product platform for energy renovating preferably large buildings
- A product platform for the low-cost market. Those buildings start at 40 m^2 and are targeted at townships. See Appendix 4 for an example of this platform's use

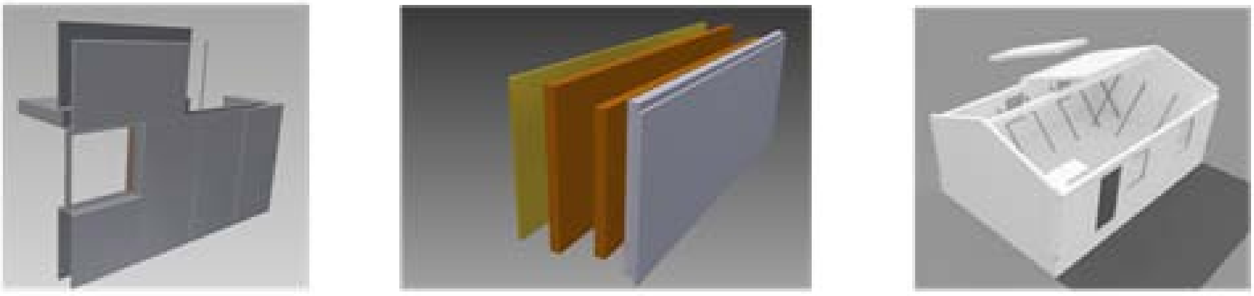

Figure 14: The product platforms of connovate – sandwich high end, insulation panels, and sandwich low-cost (connovate 2013)

From a technical point of view a lot of variation is possible within the different platforms e.g. in terms of size of the sandwich panels and windows in addition to surface colour, roughness, and aesthetics. In the high end market this is tolerated as those parameters are key drivers for sales. But on the low-cost market only a few sizes of buildings are offered and only with limited flexibility. This enforced simplicity keeps the cost of such a building very low. A price of less than 5000 € for a 40 m^2 building was realized in South Africa. None of the South African competitors was able to deliver their 40 m^2 buildings at such a high quality and still achieve that low a price.

4.1.3 ORGANIZATION AND STAKEHOLDERS

When this research project started the core team of connovate consisted of three members who managed three consulting companies and five research institutes. Later the core team shrank to two members (Arkitema and Ambercon). Figure 15 shows the key stakeholders of connovate.

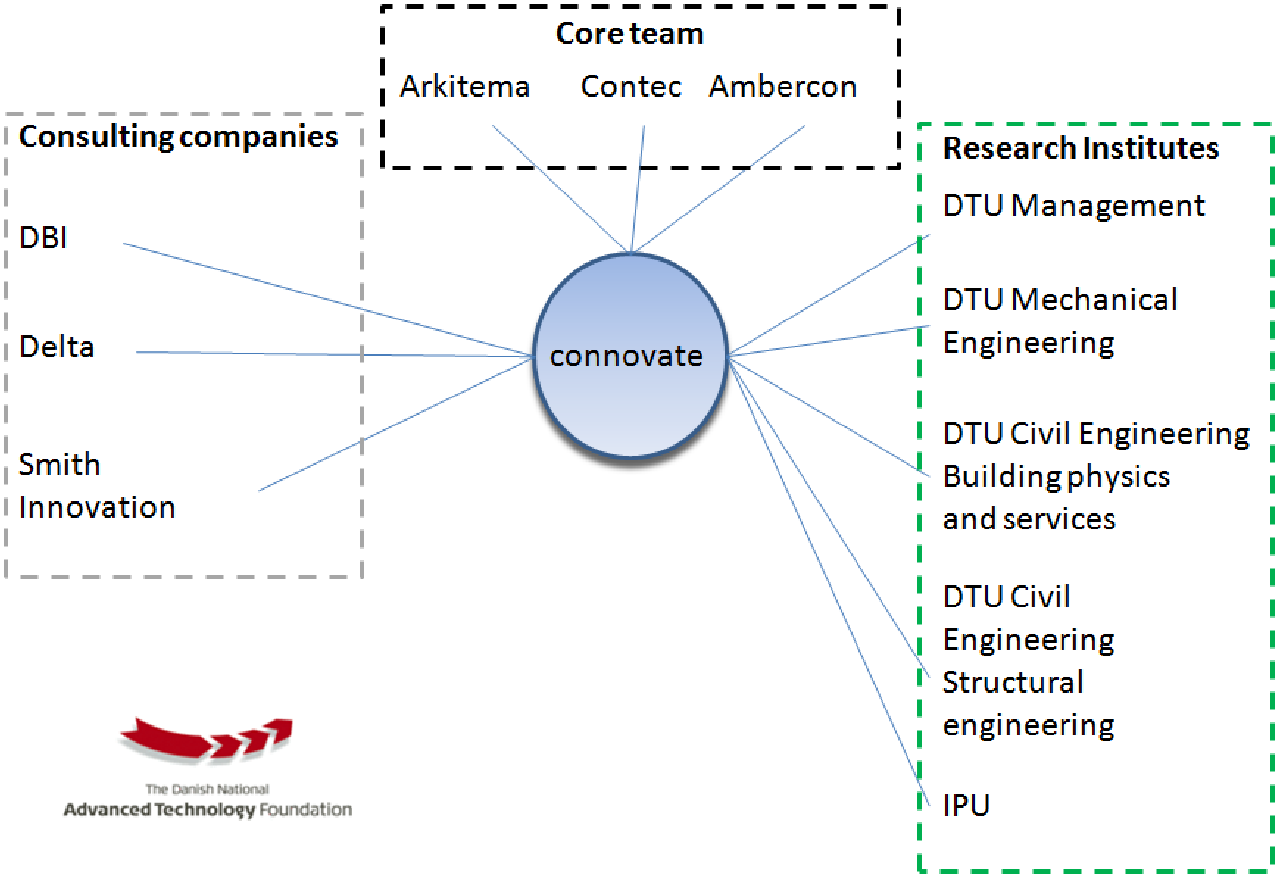

Figure 15: Key stakeholders of connovate

connovate has many stakeholders. Figure 16 shows a stakeholder map from 2012 that was presented at a product development conference in Denmark (Produktudviklingsdagen 2012). This stakeholder map does not contain authorities and municipalities as they change from area to area but nevertheless shows the complexity that has to be handled by connovate.

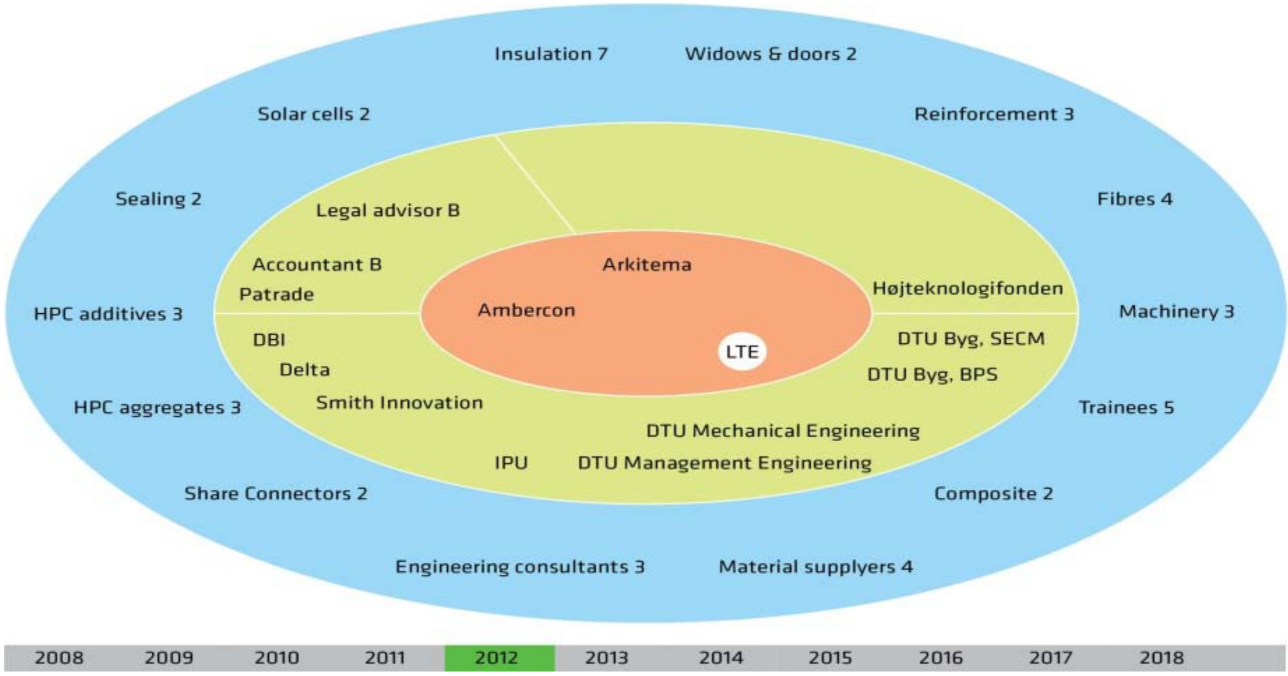

Figure 16: The stakeholders of connovate in 2012

4.1.4 VALUE CHAIN AND ORDER SCENARIOS

To find the sources of the requirements that the case company has to handle, a stakeholder map was made and also a mapping of the value chain. Porter's generic value chain model (1985) was helpful for developing the value chain as shown in Figure 17 as it looks into primary and support activities in different areas.

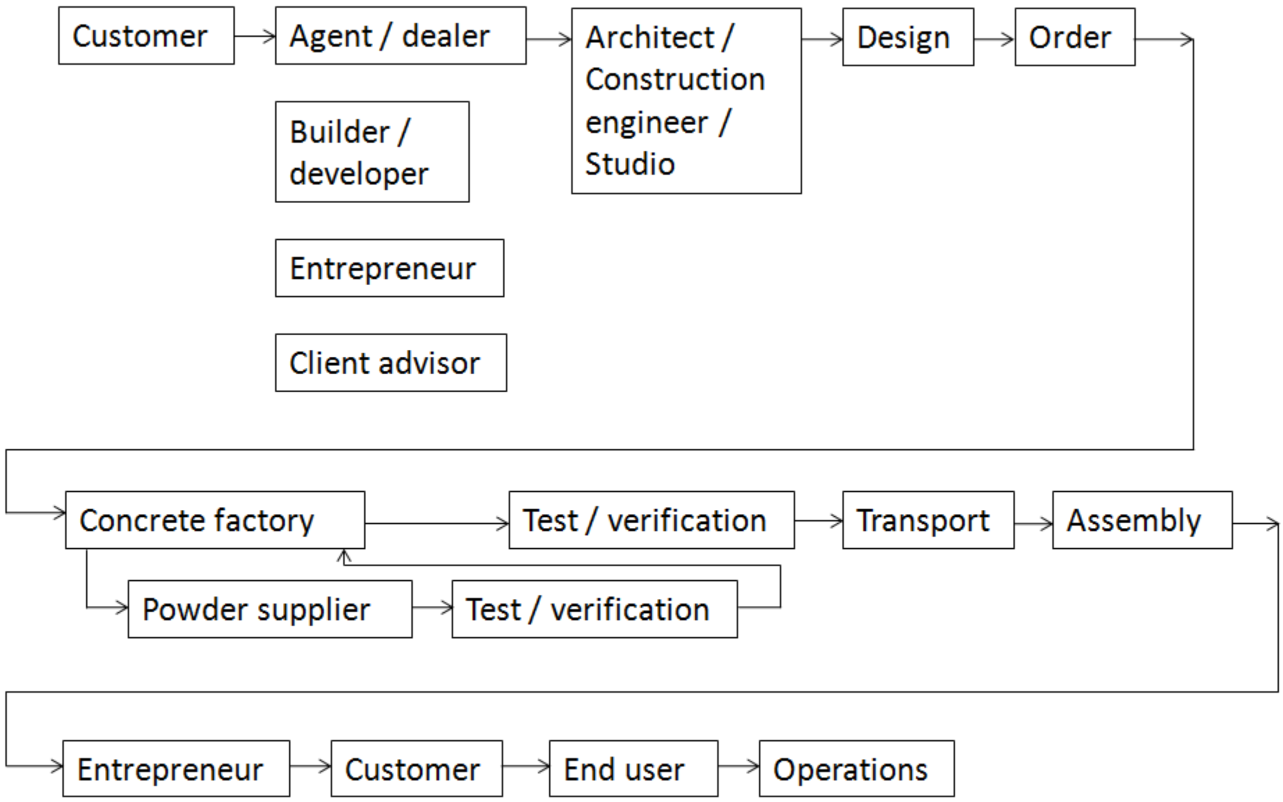

Figure 17: The value chain of the case company – one possible main scenario

The possible main scenarios of the connovate value chain / order scenarios that were identified:

1. The customer approaches connovate, as shown in Figure 17
2. connovate approaches the customer
3. Public tender / major customer. A licensee of connovate participates in a bidding round
4. Future scenario: A licensee / daughter company approaches connovate

4.1.5 INNVOVATION

In the three years that I have worked on the case project, eight patent applications have been filed of which some were already granted. The patent applications were on production processes and on technology development, e.g. a jointing solution using a steel joint as shown in Figure 18. Furthermore a mobile factory was developed. This mobile factory is considered to have a major impact on how houses are built for township dwellers in the near future as the factory can be placed on-site and driven by local labor using local material.

Figure 18: A jointing solution that was developed by connovate and the Institut for Produktudvikling (IPU) (connovate 2013)

The innovation of the case company can also be seen in other areas:

- The insulation performance of the sandwich elements in relation to their thickness is outstanding. Already today the insulation requirements from the European Union for 2020 (European Union press release 2008 and European Union 2010) can be fulfilled. When building walls with the same insulation capabilities in the “traditional way” the thickness of such a wall would be around 68 cm. connovate can achieve the same insulation results with a wall thickness of 30 cm. This corresponds to 12 m^2 or one room extra per floor of a standard one family house and allows more light to come into the building
- The surface of the HPC sandwich elements can be made in many different colors and patterns. If desired, one can even write a name or other words on the wall of his / her house. The surface can be made in a smoothness that is close to that of a mirror
- The time needed for production and construction is reduced compared to other concrete buildings
- The results of a Life cycle Assessment (LCA) show that the CO_2 production of a connovate building is optimized compared to other concrete buildings of the same size

4.1.6 REQUIREMENTS MANAGEMENT ON THE CASE PROJECT

As explained in section 2.1.1 *role of the researcher* my main task was to implement formal requirements management on the case project. The starting point was to find a suitable structure that can include all requirements of the case project in one place and that is accessible to all key stakeholders. After identifying and mapping the stakeholders (section 4.1.3) and their requirements along with the value chains (section 4.1.4) it was now essential to look at the technical requirements and their flow through the case project as this was expected to give many new insights into what a requirements structure has to be able to handle. This was done on a level that is usually used for strategic planning. The flow of technical requirements through the case project is presented in Figure 19 below.

Once the mapping of the flow of the technical requirements was done it was not difficult to create a suitable requirements structure. This structure was operational after about one year and is described in Article 1.

While this structure was used several overlapping activities were going on:

- All requirements were put into the identified requirements structure, grouped, and put into work packages that were given to the different project teams
- The requirements structure was maintained
- Monthly meetings with the project manager were held with a focus on requirements management (please note that the project manager had access to the requirements structure whenever he wanted. It was not necessary to have a meeting with me for that) and requirements management related management issues
- The project manager held regular scope follow-up meetings with the different project teams
- The literature review on requirements management and framework models was ongoing
- The interviews with other construction companies and university experts were ongoing
- The development of the RMF was initiated
- Numerous iterations of the framework were made based on reflection and the analysis of empirical data, data received at interviews, and discussions with experts and fellow academics
- The different building blocks of the framework were implemented into the case project and tested as they were developed

After a bit less than two years, one of the main goals of this research was achieved: The RMF was first introduced and later implemented, tested, and validated as a whole. Now there was an end-to-end process for formally managing requirements in at least POL-2 of the construction industry. This is described in Articles 2 and 7.

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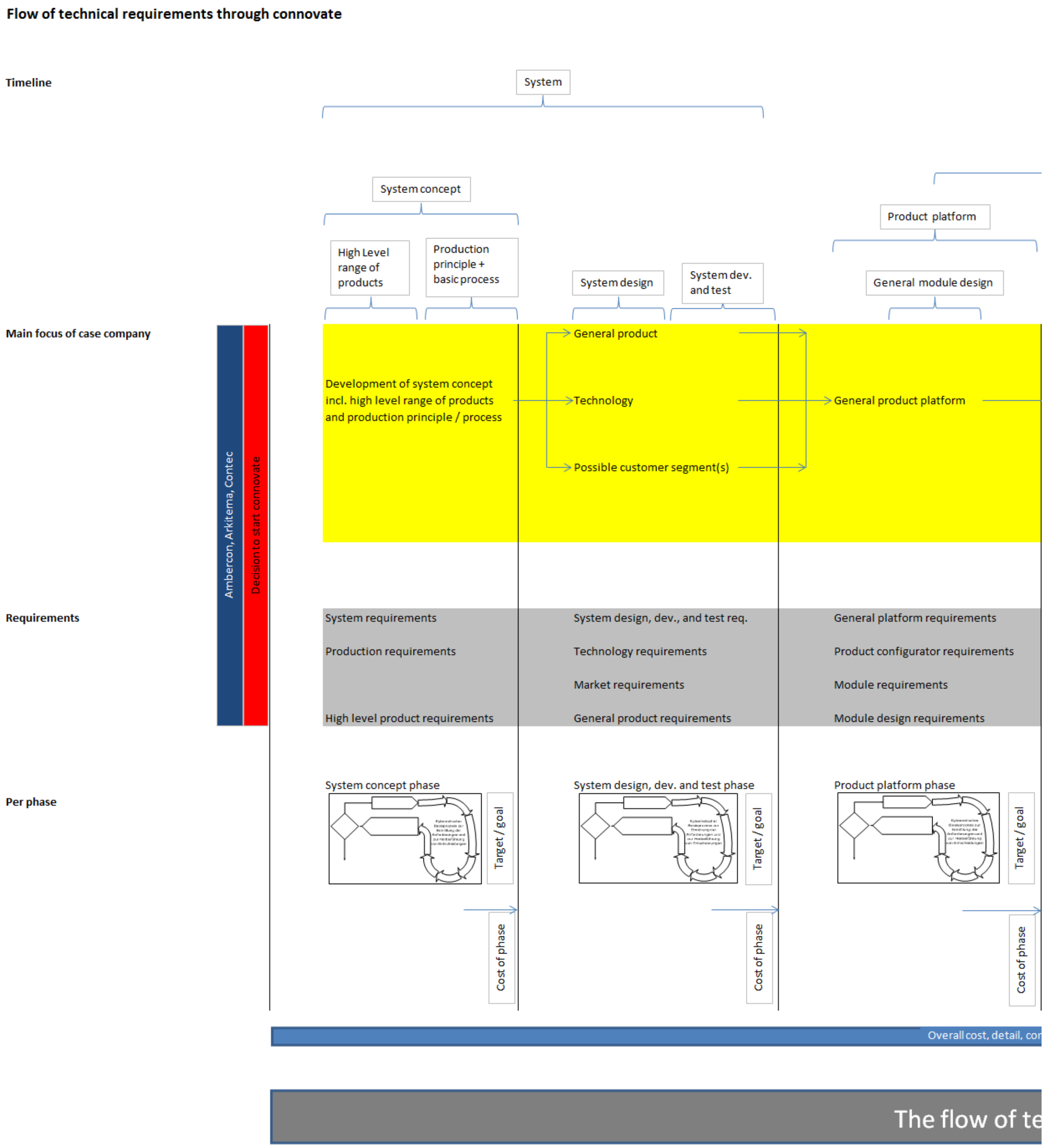

Figure 19a: Flow of technical requirements through the case project

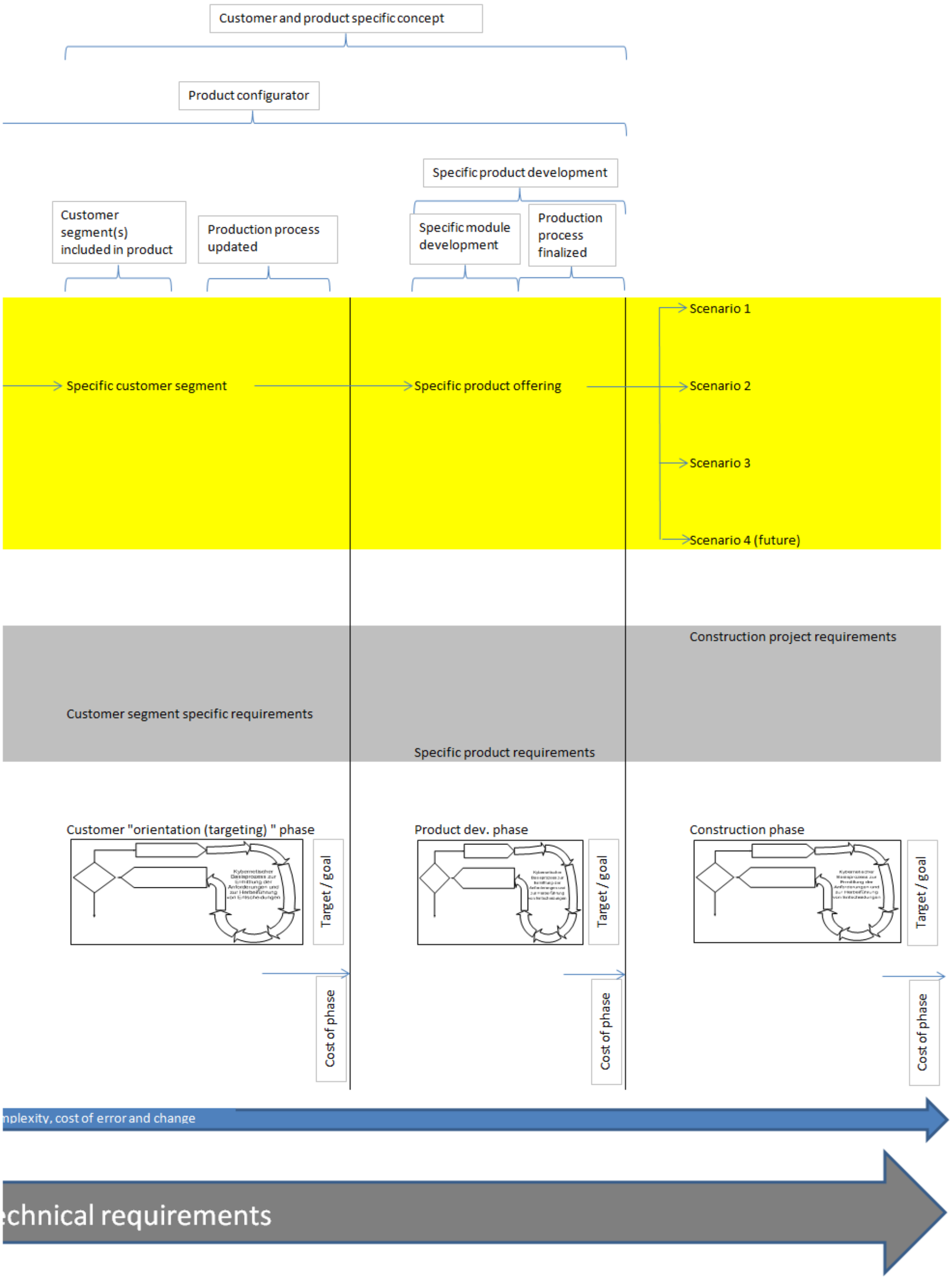

Figure 19b: Flow of technical requirements through the case project – continued

4.2 INTERVIEWS CONDUCTED AT OTHER COMPANIES

The second part of the practical basis offers a short description of the companies whose employees were interviewed. As can be seen in Figure 4, persons in fourteen companies and one authority – outside the case company – were interviewed. Three of those companies are situated in Zurich, Switzerland. The remaining companies are spread over Denmark.

As the management of all of those companies was given the promise of anonymity no names will be mentioned in this thesis. Instead, two other pieces of information will be shown in this section. That is what kinds of construction projects those companies are running and the categories of projects they have to handle on top of construction projects.

The types of construction projects that are run by the interviewed companies:

- Single family houses – a few types of houses with variants
- Single family houses – a few types of houses, some additional features can be bought for each type
- Large housing
- New Development
- Office buildings
- Large office buildings
- Large hotels
- Insulation of old buildings
- Infrastructure e.g. bridges, highways, streets, metro, railroad
- Plant and stable construction
- Energy, oil, gas, off-shore, foundations for wind turbines

The categories of projects the interviewed construction companies are running besides construction projects:

- Product development
- Product platform development
- Technology development
- Land development
- Engineering
- Environmental
- Analysis
- Management, IT, economy, and change management
- Quality improvement
- Transportation
- Construction management

Some of the above listed categories of projects have triggered further categories of requirements in the case projects' requirements structure. In section 5.7.3 further information concerning the interviewed companies will be given.

4.2.1 REQUIREMENTS MANAGEMENT AT THE INTERVIEWED COMPANIES

For both POL-1 and POL-2 companies I discovered that no tools for managing requirements were used. Also none of the companies had an end-to-end process for managing requirements in place even though some claimed to focus on life cycles.

The companies repeatedly building the same kind of building (POL-2) were using standard work descriptions and were managing their projects by deviations. A deviation is when a customer wants to have a wooden floor made of cherry tree instead of ash tree for example. Apart from the deviations that needed to be incorporated into the planning, those companies knew exactly what was supposed to happen on any given day of a construction project as detailed plans (standard work descriptions) were being used.

The companies building something new (POL-1), something that they have not built before, did, for obvious reasons, not have standard work descriptions. Usually one would expect them to compensate for that by doing detailed planning and having a clear process for project scope management. But this was *not* the case. During the interviews I saw an example where 1.6 billion DKK was given to a project and the project manager at the time he received the money did not even know, yet, what the building he was supposed to build should look like. Another example is a 5 billion DKK project where requirements were tracked in an xls.-sheet. Admittedly the management team of this project was in better shape than the other interviewed companies building something new in terms of managing requirements but they still did not use a tool but an xls.-sheet. How can the problem of change or inheritance of requirements (parent – child relationships) be overcome in an xls.-sheet?

Article 2 contains a table that shows the gaps that were identified during interviews with 12 companies and one authority.

4.3 CONCLUSION OF PRACTICAL BASIS

The purpose of describing the practical foundation in this thesis was to give the reader a better understanding of what this research was based upon.

The practical basis was divided into two parts. In the first part a detailed description of the case company and different aspects to it was given. Special emphasis was put on the way requirements were managed on the case project.

The second part of the practical base was used to give an initial introduction of the interviewed companies, what types of construction projects they are running, and the categories of projects they engage in in parallel with construction projects.

The practical basis with all its extreme cases gave plenty of data that were used to answer the four research questions (section 1.4). Here the hypothesis was that a framework working in extreme situations should perform stable in standard situations, too.

5 RESULTS

The results of this research are presented in this section. The results are described in seven scientific articles and sub-section 5.7 “Further results not described in articles”. Three of the articles were presented at conferences and four were targeted at scientific journals. The articles are labelled “Article 1” to “Article 7”. Table 2 in section 2.2.5 shows how the articles cover the different research questions. The numbering of the articles indicates the order in which the process of writing them began.

The first article contains a structure for managing requirements on the case project. Articles 3 and 6 are about the application of product platforms in construction. Article 5 looks into product architecture and Product Lifecycle Management (PLM) systems. Article 4 describes a model that quantifies the impact of new requirements on an existing product architecture. This can be used for accepting or rejecting a requirement based on a numeric value. The knowledge gained when writing those articles helped writing Articles 2 and 7 that describe the RMF, its implementation, and validation.

Expressed in pictures the results section describes the journey from here... (Figure 20):

Figure 20: A failed fire test of a HPC sandwich panel tested at Dansk Brand- og sikringsteknisk Institut (DBI)

...to there (Figure 21):

Figure 21: Villa Vid. A single family house made from HPC sandwich elements (connovate 2013 and Ingeniøren 2011)

5.1 ARTICLE 1

Title: "Structuring Requirements in a Multi-Project Environment in the Construction Industry: A Life Cycle Perspective" (Wörösch, M. 2012)

Research question(s) answered in this article: This article contributes to main RQ1: "What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?" and is a pre-requisite for being able to answer the second main research question: "How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?"

Contribution to the PhD research questions: For writing Article 1 it was necessary to look into where requirements for construction projects originate from (the identified categories are shown in section 5.7.1), how the requirements gathering and handling is typically done by different construction companies, what obstacles construction companies face (the obstacles are shown below in section 5.7.2) in relation to requirements management, and how they overcome those obstacles. Article 1 combines this knowledge and presents a "future proof" structure for managing requirements on the case project.

Research method: The research method for most of the described articles was – to different degrees – action research (section 2.2.1) on a case project (section 4.1) in combination with interviews (section 2.2.2) and extensive literature studies (section 2.2.3). As this was already explained in this thesis it will not be described again.

Results: In Article 1 a feasible (practical; living up to the needs of the project) structure for managing requirements on a building project in the construction industry was presented (please see Figure 8 of Article 1). This structure tries to consider the entire life cycle of a building and not only the phases until the end of a building project. It was the first time a basic implementation of formal requirements management on a building project was described.

Other results of this article:

- An overview of the different types of requirements that have been found on the case project
- Four different scenarios of the value chain of the case project were identified. The most common scenario was described in Article 1. A brief description of all four scenarios can be found in section 4.1.4 of this thesis
- Four different life cycles were identified, applied, and described:
  a) The life cycle of a building that is produced by the case project
  b) The phase model for the case project
  c) The life cycle of a requirement, and
  d) The life cycle of technology

A schematic comparison of those life cycles was made. This helped prioritize resources for the case project

- The myth that all requirements are covered by norms and standards was proven to be wrong
- Key sources for this research (Fernie et al. 2003, Girmscheid 2010, and Krönert 2010) were found and a research cooperation was started with professor Grimscheid. This cooperation resulted in mutual visits and my external stay at the ETH in Zurich, Switzerland. This research cooperation was and is still very fruitful

5.2 ARTICLE 2

Title: "A Requirements Management Framework for Construction Companies Offering Pre-defined Products" (Wörösch, M., Bruun, H. P. L., Howard, T. J., and Mortensen, N. H. 2014)

Research question(s) answered in this article: This article is the main contribution of this research and contributes to all four research questions (RQ1-4). It builds upon main RQ1: "What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?" and directly answers main RQ2: "How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?" Furthermore, Article 2 begins giving an answer to main RQ3 "How can the developed requirements management framework be implemented and used on the case project?" and supporting RQ4 "Can the effectiveness and generalizability of the requirements management framework be demonstrated and how can they be validated?"

Contribution to the PhD research questions: For being able to write Article 2 a requirements structure had to be identified (Article 1), and knowledge had to be gained on product platforms (described in Articles 3 and 6), product architecture (Article 5), and how to decide whether to incorporate a new requirement on an existing product architecture or not (Article 4). Table 2 in section 2.2.5 shows how the different articles contribute to the research questions.

Research method: Please see section 5.1 (outline description of Article 1) of this thesis.

Results: "This paper first reviews the literature related to requirements management and then assesses the state of the art throughout the Danish construction industry. Based on the summary of these reviews constructed from 30 interviews over five interview rounds, a comprehensive approach to formal requirements management is proposed. The approach takes important elements such as:

- A life-cycle perspective
- Addressing the gap of not having an end-to-end process for handling requirements in construction in a pragmatic way
- Ensuring major activities such as stating goals at the start of the project and comparing achieved results to the stated goals at the end of the same project
- Managing, testing, verifying, and validating requirements
- Seeking knowledge from other companies within the network

from best practice, chosen due to their successful application in other projects and industries. The interviews revealed that this is often only done partly and sometimes not at all (as shown in Table 1 in Article 2)" (Wörösch et al 2014, p. 3).

Article 2 also contains the *RMF* that has its intended use on building projects. This framework has its strength in the structured approach for managing requirements and in being able to handle building projects in combination with different sorts of development projects.

Article 2 presents a conceptual framework (not on checklist level, yet) that consists of building blocks (see Figure 22). Those building blocks are described in detail and are intended to be of help to project- and requirements managers, once construction companies start using them, on construction projects. The article also contains the first results of the implementation and validation of the framework.

Yang et al. (2012, p. 114) state: "Many studies have indicated that one of the major challenges in project / construction management is in the definition and management of project requirements". The results described in Article 2 can be used to overcome this major challenge.

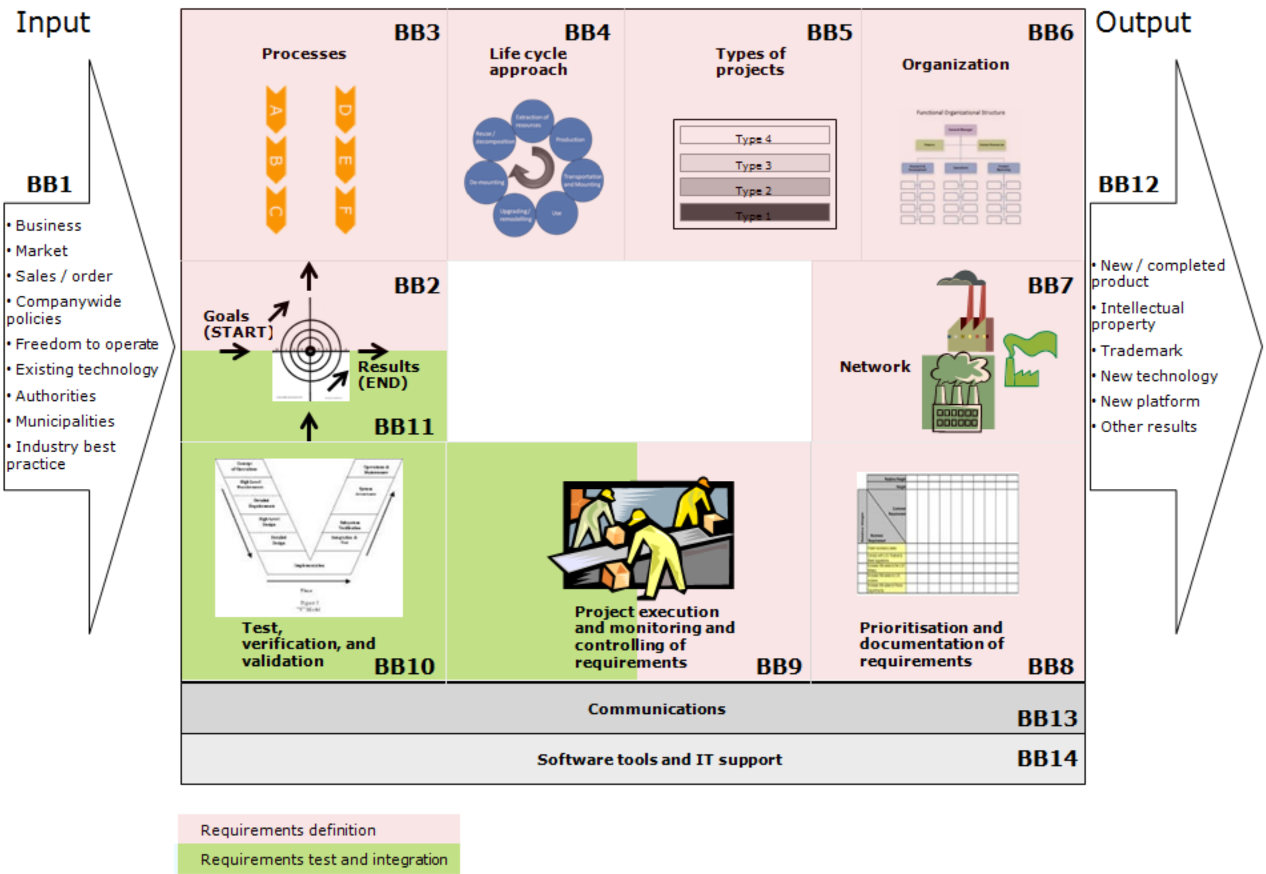

Figure 22: A proposed framework for managing requirements in the construction industry (Wörösch et al. 2014, p. 9)

A general explanation

The difference between the RMF and BIM is that BIM can be used to describe the requirements of a construction *object*, i.e. the part of a building or a whole building, but not to capture *all* requirements on a project.

The difference between LEAN and the RMF is that the latter has no special focus on improvement, for example, the improvement of cycle times.

The difference between Total Quality Management (Martínez-Lorente et al. 1998) – in short TQM – and the RMF is that TQM focuses on an organization-wide effort to make a climate that fosters continuous improvement. The RMF focuses on single projects and not on the entire organization.

Nevertheless, the RMF should work well in an environment where BIM, LEAN and TQM are applied. In fact, one could argue that TQM cannot be done without formal requirements management.

5.3 ARTICLE 3

Title: "Product Platform Considerations on a Project that Develops Sustainable Low-cost Housing for Townships" (Wörösch, M., Bonev, M., Mortensen, N. H. 2013)

Research question(s) answered in this article: This article helps in answering main RQ1: "What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?" and is a precondition to answering main RQ2: "How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?"

Contribution to the PhD research questions: Article 3 contributes to this research by demonstrating that it is possible and can be profitable to use product platforms in construction. It describes the use of modularity on a 40 m^2 house designed for townships in South Africa. This insight was ultimately used to enhance the requirements structure that is described in Article 1 and has thereby contributed to making a requirements management framework that can handle platform and modularization aspects.

Research method: Please see section 5.1 (Article 1) of this thesis.

Results: Article 3 shows that about 1.6 billion people around the world live in sub-standard housing and over 100 million are homeless. The article shows that this housing problem can be solved as the price of 4.927 € (exchange rate from 25th of December 2012) for a 40 m^2 house made from HPC sandwich elements is affordable for many governments, NGOs, and some township dwellers. The article also mentions that such a house can be built in eight hours once the foundation is in place and the sandwich elements are ready for assembly.

Article 3 concludes that the product platform approach is a valid strategy for meeting the low-cost housing demand of developing countries.

Other results of this article: Writing Article 3 resulted in a charting of the product platforms that are used in the case company, as shown in Figure 23, and the requirements related to them. Besides, the idea of a mobile factory that can be set up on the building site and that can use local labour and resources (99%) is likely to have a major impact on society. An example for that could be Haiti where people two years after losing their homes still live in tents. Here it would make sense to apply the mobile factory.

Another result was the knowledge transfer from the low-cost to the high end platform. It showed ways to save money and enforced efficiency on the high end platform.

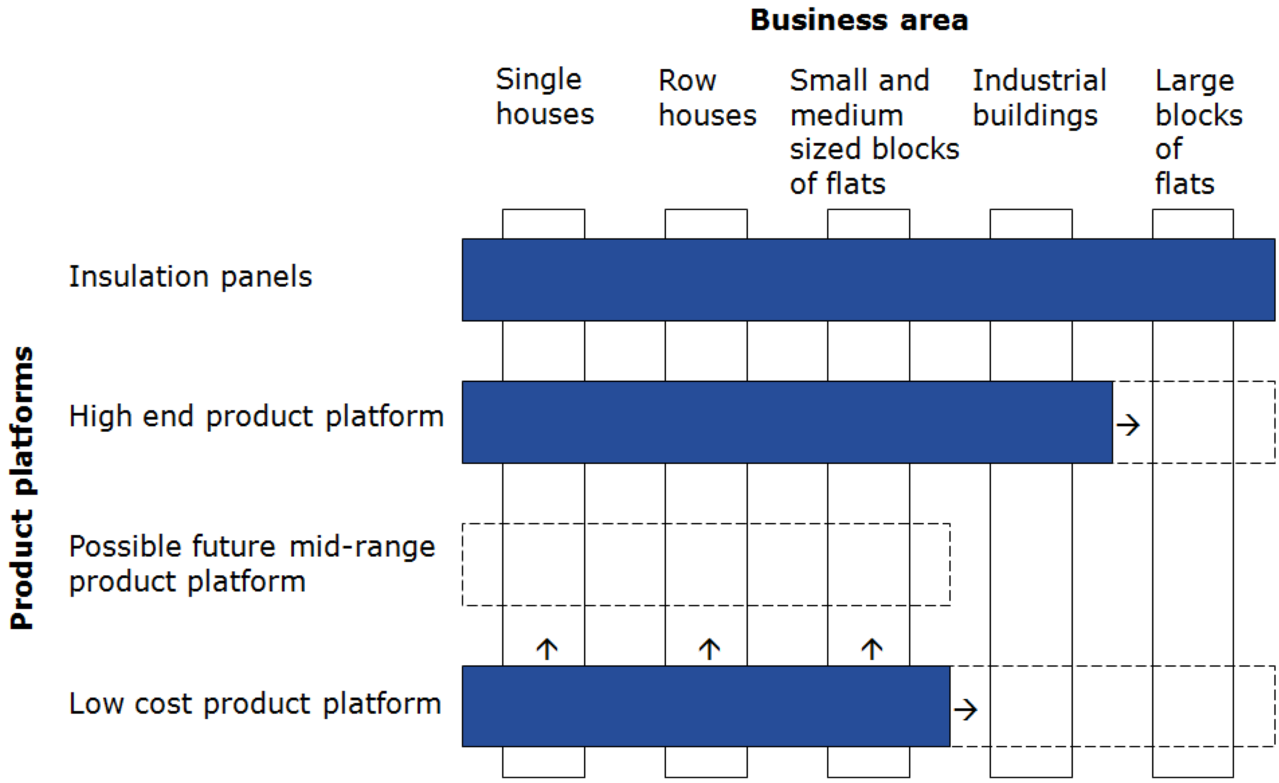

Figure 23: The product platforms that exist in the case company (Wörösch et al. 2013, p. 2)

5.4 ARTICLES 4 & 6

Titles: "Extending Product Modeling Methods for Integrated Product Development" (Bonev, M., Wörösch, M., Hauksdóttir, D., Hvam, L. 2013) and "Utilizing Product Platforms in Industrialized Construction" (Bonev, M., Wörösch, M., Hvam, L. 2014)

Research question(s) answered in this article: These articles help in answering main RQ1: "What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?" and are a necessity for answering main RQ2: "How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?"

Contribution to the PhD research questions: Articles 4 and 6 contribute to this research by (1) providing a model that can quantify the impact of new / updated requirements on an already existing product architecture and thereby help the project manager and designer take decisions on whether a new / changed requirement should be implemented or not and (2) by extending the model to a platform framework in industrialized construction. We chose to call this model "The product requirements development model". In the context of this research this model can be seen as a supporting model. Otherwise it deserves to be treated as a stand-alone model.

The reason for writing those articles was that the way of handling new / updated requirements for an existing product architecture can have an influence on the requirements structure (as presented in Article 1) and on the engineering change management process that was described by Jarrat et al. (2011) along with Terwiesch and Loch (1999). Moreover, not being able to handle new requirements or update existing requirements is a serious obstacle and therefore part of main RQ1.

The difference between Article 4 and 6 is that Article 4 is a conference article that presented the model on a very limited number of pages. During the ICED 13 conference this article was used to get feedback on the model itself and on our way of thinking. Then the received feedback was incorporated and the theory part of the article was extended with, for example concurrent approaches for productivity improvement. Those concurrent approaches were subsequently put in relation to product platforms and manufacturing strategies of a precast manufacturer (Article 6).

Research method: Literature research and action research for Article 4 and literature research, case study, and supporting interviews for Article 6.

Results: Article 4: By combining several established modeling techniques, such as the DSM (Eppinger and Browning 2012) and PVM (Hvam et al. 2008) methods into a new model – The product requirements development model – the individual drawbacks of each method could be overcome. Based on the UML (2011) standard, the model enables the representation of complex hierarchical relationships in a generic product model. At the same time it uses matrix-based models to link and evaluate updated requirements to several levels of the product architecture and to illustrate how these requirements have an upstream (towards stakeholders) and downstream (towards production) effect on the product architecture. An overview of the model is shown in Figure 24.

Article 6: This article first describes a charting of the manufacturing strategies that are used in the precast industry and presents a mapping of some of the requirements that were encountered on the case project before showing that the product platform approach can be used in and is relevant for industrialized construction. Article 6 also presents a framework for platform development and shows the differences of the axiomatic design approach to the DSM approach.

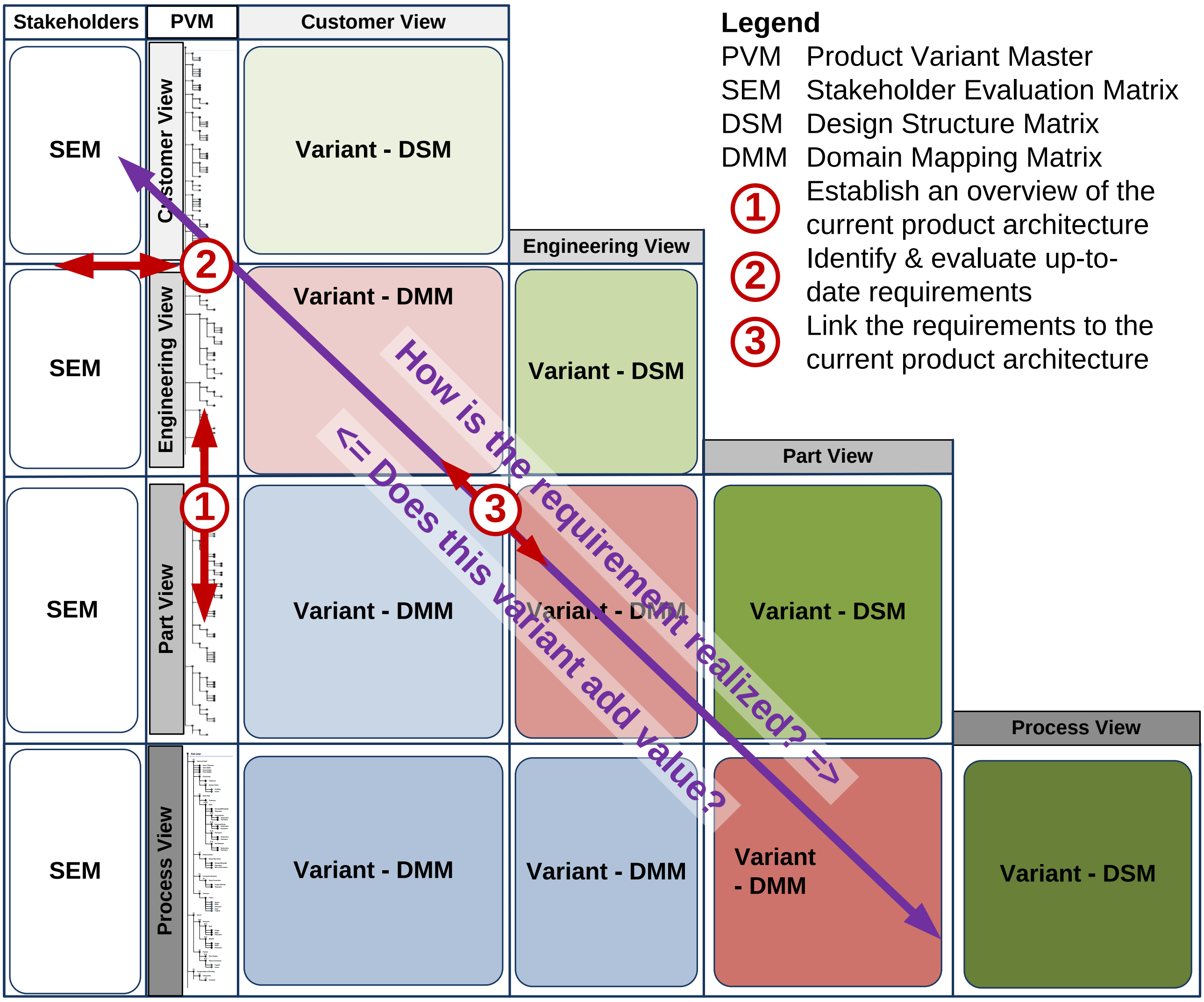

Figure 24: The product requirements development model – Overview (Bonev et al. 2013, p. 6)

5.5 ARTICLE 5

Title: "PLM System Support for Modular Product Development" (Bruun, H. P. L., Mortensen, N. H., Harlou, U., Wörösch, M., Proschowsky, M. 2013)

Research question(s) answered in this article: This article indirectly contributes to answering main RQ1: "What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?" and main RQ2: "How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?"

Contribution to the PhD research questions: The work carried out when writing Article 5 adds to this research by providing insight into how to model and build up product architectures. It was examined how requirements originating from the product architectures of the case company influence the requirements structure that was introduced in Article 1. On top of that it was checked that the possible use of tools as PLM and the employed product architectures are not proving obstacles to the formal requirements management of the case project.

Research method: Please see section 5.1 (Article 1) of this thesis.

Results: Article 5 shows a description of an empirically tested approach using a visual product architecture representation in combination with a PLM system to support the development of a product family of complex products. This is done in order to have the best of both worlds: Utilize visual architecture descriptions to create overview, improve communication and collaboration, and to support the creation of modular product structures; and to utilize a PLM system to manage and integrate product information from the architecture descriptions effectively.

The results from the study encompass new PLM capabilities for handling multiple product structures, visualising multiple architectural views on products, controlling interfaces, and quantifying and communicating the status and progress of product-related resources.

Other results of this article that are worth mentioning: The implementation of the approach of using a visual architecture description in combination with a PLM system showed some promising qualitative results. By interviewing the members of the management team and the 14 different design teams of a case company, the following statements could be reported as results of the implemented approach:

Management

- Design readiness much clearer earlier in the projects
- More transparent cost deviations
- Design progress more accurate to measure on a weekly basis

Designers

- Very little extra work when thinking in architectures for a family compared to single product development
- All engineering teams have access to the same single source of information
- Easier to develop and evaluate module concepts in the early design phases
- More effective reviews

5.6 ARTICLE 7

Title: "Validation of the Requirements Management Framework for Construction Companies Offering Pre-defined Products" (Wörösch, M., Mortensen, N. H. 2014)

Research question(s) answered in this article: This article gives an answer to main RQ2 "How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?", main RQ3 "How can the developed requirements management framework be implemented and used on the case project?", and supporting RQ4 "Can the effectiveness and generalizability of the requirements management framework be demonstrated and how can they be validated?" As main RQ2 builds upon main RQ1 this article indirectly helps in validating main RQ1.

Contribution to the PhD research questions: Article 7 adds to this research by validating the RMF that was a result of answering main RQ2. Besides, the article describes the implementation and use of the RMF on the case project and thereby concludes the chain of arguments (see Figures 1a and 1b) of this PhD thesis.

Research method: Please see section 5.1 (Article 1) of this thesis.

Results: The main results described in Article 7 are:

- A description of the steps for making and validating the RMF as presented in Figure 6 of this thesis
- Qualitative and quantitative validation of the RMF
- A description of the application of the RMF to a test house building project
- The conclusion of the expert peer reviews
- An updated version of the RMF. This new version of the framework is shown in Figure 25 below
- A description of the different approaches to requirements management of the Danish and Swiss companies that participated in the interviews

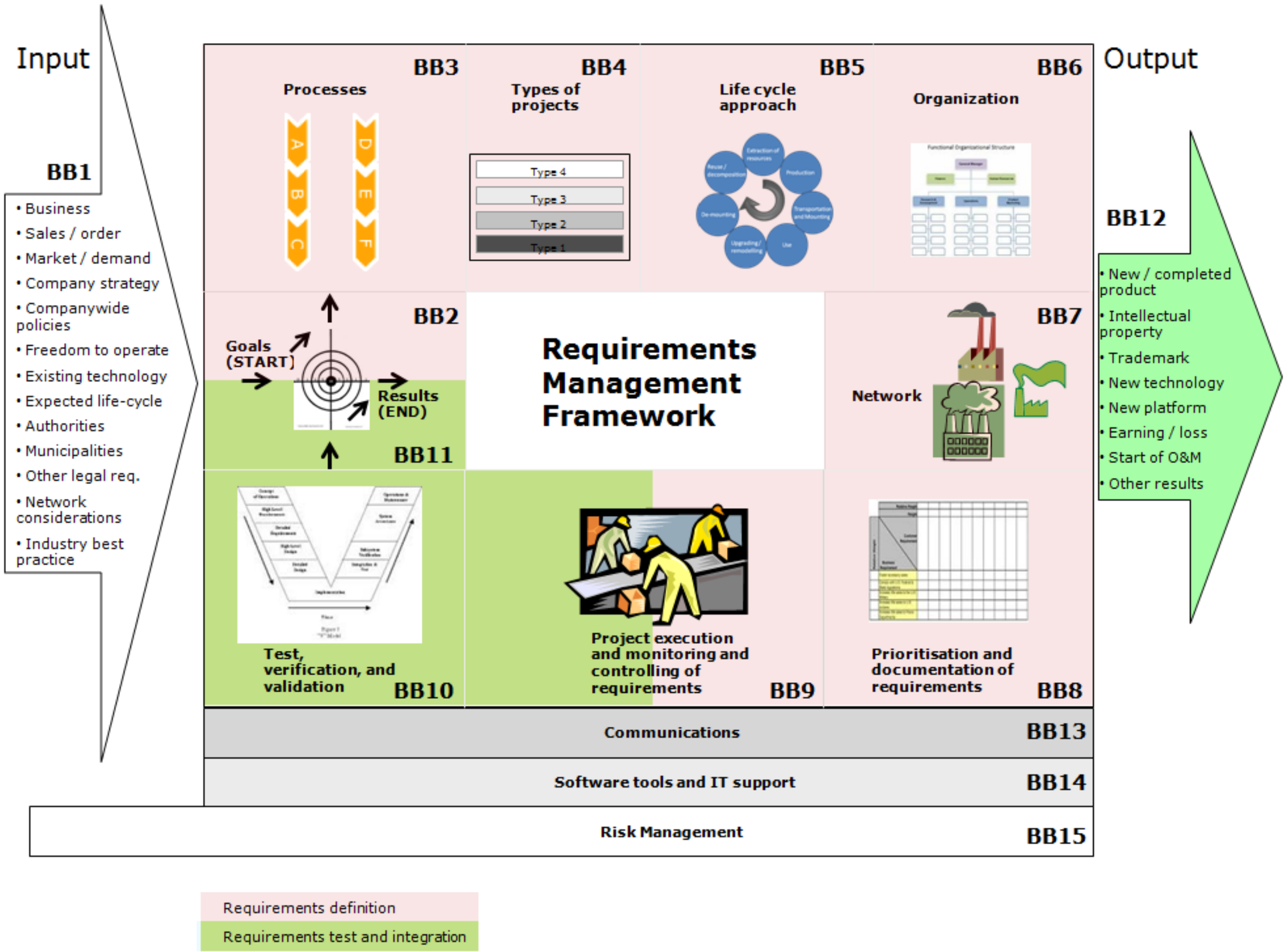

Figure 25: An updated version of the RMF (Wörösch and Mortensen 2014, p. 21)

Other results and observations of this article that are worth mentioning: In his article "Validation in Inquiry-Guided Research: The role of exemplars in Narrative Studies", Mishler (1990, p. 416) argues that for "inquiry-guided research the standard approach to validity assessment (e.g. measuring variations on quantitative dimensions or "testing" the significance of the findings with statistical procedures) is largely irrelevant to our concerns and problems". Mishler (1990, p. 436) re-formulates *validation* as "the social construction of scientific knowledge." With this reformulation, the key issue becomes whether the relevant community of scientists – and practitioners – evaluates the reported findings as sufficiently trustworthy to rely on them for their own work. As this research is inquiry-guided I see Mishler (1990) as key and use his definition to level expectations with the reader, i.e. even though some quantitative validation was done the main part of the validation was of a qualitative nature as that makes most sense. Also – in my opinion – getting a "Yes, I would apply the RMF to my project / research" is a better validation of the framework than proving that some percentage of the project budget and time schedule of the test house building project was cut off.

5.7 FURTHER RESULTS NOT DESCRIBED IN ARTICLES

When looking at Figures 1a and 1b one can see that main RQ1 (What are the central phenomena posing a challenge to construction companies when gathering requirements and managing them end-to-end?) was not covered by an article (there was simply not enough “meat on the bone” to write an article on the subject). Therefore it will be described in this sub-section.

Figure 1a shows that both the requirements management process and the sources (categories) of requirements can comprise obstacles / challenges for not using formal requirements management. Section 4.1.6 and Article 1 contain a brief description of how requirements management was done on the case project. Therefore, no further explanation of the requirements management that was used on the case project will be given here. As the interviewed companies have many different ways of managing requirements they will also not be described here. What is missing is a description of the sources (categories) of requirements as well as a list of the obstacles / reasons for not using formal requirements management that were discovered during the literature search, interviews, and analyses:

5.7.1 CATEGORIES OF REQUIREMENTS

Kamara et al. (2002) have identified six types of project requirements in the construction industry. They divide requirements of a construction project into: client requirements, site requirements, environmental requirements, regulatory requirements, design requirements, and construction requirements. Furthermore, they give a description of what each type of project requirement contains. This is the most comprehensive description that I could find during my literature searches. Therefore it is used as a base for this research. Kamara et al.´s types of project requirements are shown in the grey font in the list below. The new types of requirements and the additional content that had to be added to the existing types of requirements in Kamara et al.’s overview in order to cover the requirements of the case project were written in black font:

- Client requirements: Life cycle related requirements before Operations & Maintenance, requirements originating from changes in society
- Site requirements
- Environmental requirements
- Regulatory requirements: Freedom to operate
- Design requirements: Product requirements
- Construction requirements: Project management related requirements
- Production requirements: Requirements for the production process, requirements for the production of material and (pre-fabricated) elements
- Product platform requirements: Requirements originating from having one or more product platforms (often related to product architecture, re-use of knowledge and documentation, and market segments), system requirements
- Technology requirements: Requirements being triggered by new technology / the applied technology

- Organizational requirements: Depending on how the project and related companies are organized different requirements are likely to surface
- Personal requirements: This is often neglected. But requirements coming from appraisal talks and managers' bonus schemes have an impact on the project. Especially when those requirements are contradicting other requirements or changing the priority of requirements
- Business requirements: Market, sales, order, competitor requirements
- Quality requirements: Processes, industry best practice, general quality and certification, Lessons Learned
- Management requirements: Requirements imposed by the management of a construction company

As one can see, eight new types of requirements and additional content to existing types of requirements had to be added in order to satisfy the need of the case project.

5.7.2 OBSTACLES/REASONS FOR NOT APPLYING FORMAL REQUIREMENTS MANAGEMENT

Obstacles / reasons found during literature searches:

In 2009, Yu et al. (p. 374+375) confirmed the challenges that were stated by Alexander and Stevens in 2002:

- "Gaps between people
- Time to work out a good requirements structure
- Expected effort and time taken
- Requirements effort throughout the life cycle
- Allowance for change and feedback
- Allowance for user's participation and expression of feelings"

In 2013, Yu and Shen (p. 225+226) published an updated list containing more obstacles:

- "Inexperienced clients in requirements management
- Inadequate identification and representation of needs and requirements during the development process
- Unstructured approaches for requirements management
- Misunderstanding and misinterpretation of client needs and requirements
- Communication gaps between participants in requirements management
- Insufficient time to work out a good structure for requirements management
- Inadequate requirements effort throughout the life cycle
- Lack of documentation on changes, and feedback for requirements management
- Lack of users' participation and lack of a voice"

Kristensen (2011) added the following points (to which not everybody in construction seems to agree):

- No will to improve
- The construction industry has reached its peak

Note: Kristensen was mainly researching the Danish construction industry.

Obstacles / reasons stated during interviews:

- Lack of knowledge of a requirements management process
- Lack of knowledge concerning systems engineering
- Lack of knowledge concerning the V-model as originally published by Blanchard and Fabrycky in 1998
- Culture / no industry best practice
- Little / no time to handle requirements. Often done by the project manager on the side
- No requirements manager allocated
- No resources
- Lack of training
- No courses / education
- No application of processes in general → Focus on craftsmen and customers instead (mentioned by some of the small companies)
- Short project time
- Little development
- No pressure from customers
- No pressure from competitors
- Sheer number of requirements that have to be managed – lack of overview
- Stakeholders who have to be considered

Obstacles / reasons as a result of data analysis:

- Little discipline of some people in the construction industry (This is aligned with Fernie et al. (2003) but disputed by other scientists)
- Unstructured approach (the approach to requirements management was better in Switzerland than in Denmark)
- Lack of planning and risk analysis
- No tool support / .xls at best
- No tradition / time available for learning from other fields
- Universities do ill-equip their students e.g. M.Sc. students in engineering do not know the V-model
- No real follow-up from industry organizations and government on delays and related cost for society
- No punishment for non-performance

When looking at the above list of obstacles one can better understand why formal requirements management has not been implemented in the construction industry earlier. The list also indicates that there still is a long way to go for construction companies that actually want to improve in this area.

5.7.3 WHAT COMPANIES WOULD APPLY THE FRAMEWORK?

A lot of data was collected about the interviewed companies. Those data can, among other things, be used to display which of the interviewed companies and authority would / would most likely use / not use the RMF – sorted by turnover, size of their biggest project in m^2, size of their biggest project in MDKK, and number of employees.

Due to non-disclosure agreements only two pieces of information will be displayed in this thesis: Figures 26 and 27 show the interviewed companies and authority that would / would most likely use / not use the RMF sorted by the size of their biggest projects in m^2 and MDKK. Adding the turnover and number of employees to the already presented information would disclose too much.

Figures 27 and 28 should be viewed in relation to Figure 4. The same letter represents the same company.

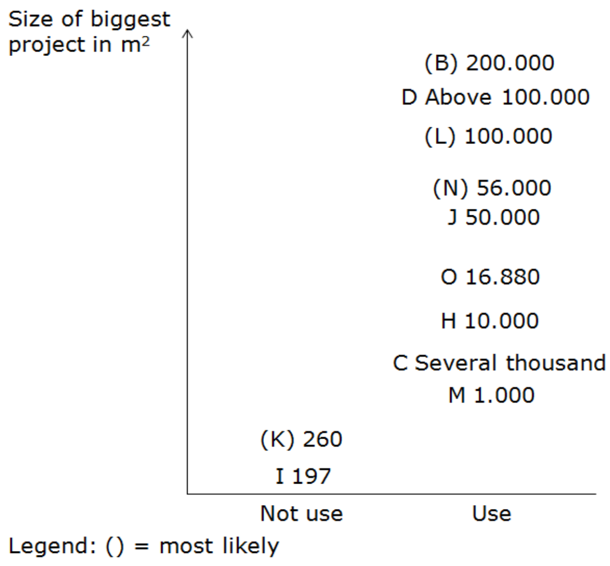

Figure 26: Interviewed staff at companies and authority that would (most likely) use / not use the RMF sorted by the size of their biggest projects in m^2

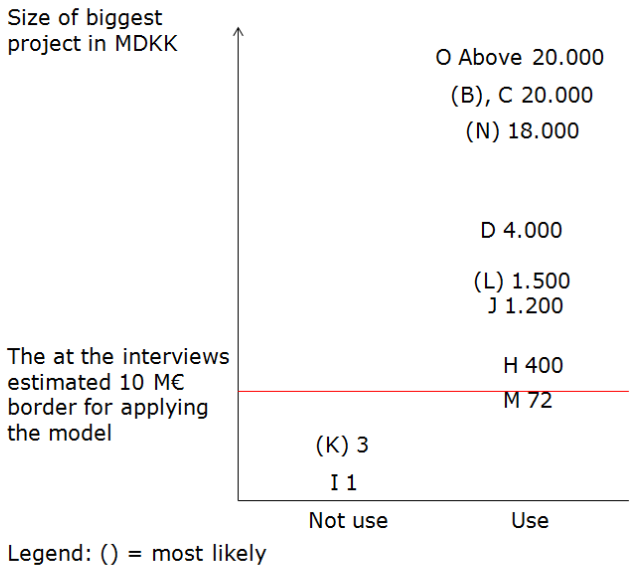

Figure 27: Interviewed staff at companies and authority that would (most likely) use / not use the RMF sorted by the size of their biggest projects in MDKK

Concerning "most likely": All interviewed staff stated that the RMF is grounded in reality. Nevertheless, the staff at one small company (K) would probably not use it as using *any model or new process* would take away focus from craftsmen and customers. This exposes a low level of maturity of the company in general and not a weakness of the framework.

Employees at some of the large companies (B and L) would most likely use the framework but would like to see it working in some other large companies before. They also stated that the RMF has to be more detailed (on checklist level) before they would use it. None of the interviewees saw an obstacle in making checklists for the different building blocks of the framework and the effort related to that. Company "N" stated that they have a very complex, but well working, management system in place and would therefore wait for the next major update of this management system before introducing the framework. As no date was put on that major update and many things can happen until then their answer was therefore that they would "most likely" use the framework.

During some of the initial interviews company experts estimated that applying the framework would give the biggest benefit for projects costing 10 M€ and above. After having conducted all interviews this picture seems to be unchanged as can be seen when looking at the red line in Figure 27.

An additional observation from the conducted interviews: There is a clear correlation between companies' willingness to use the RMF and running other categories of projects (described in section 4.2) besides construction projects. As soon as companies are running other projects parallel to running construction projects they are more willing to use the RMF.

5.7.4 CONCLUSION OF RESULTS

The results of this research clearly show that it is possible and beneficial to apply formal requirements management to at least POL-2 of the (Danish and Swiss) construction industry. This was demonstrated by developing and applying (1) a requirements structure that can be used for construction projects and (2) a RMF that focuses on the management of requirements in construction projects.

Both the requirements structure and the RMF were successfully tested on real construction projects.

The validation of the RMF had the result that some of the interviewed people actually would use the framework for their work and the benefits of using the framework are expected to be biggest on projects costing around 10 M€ and above.

In order to ease the life of construction project managers, a supporting model – The product requirements development model – that can quantify the impact of new / updated requirements on an already existing product architecture was developed and made public.

The results chapter was rounded up by showing newly identified categories of requirements on construction projects and obstacles / reasons for not applying formal requirements management. This means that results concerning all research questions were obtained. What is left is a look at the conclusion and research that still needs to be done.

6 CONCLUSION

This section summarizes the findings of this research. It starts with a description of the research findings divided by the research questions. Then it evaluates the achievement of the goals of this research before explaining the core contributions and concluding with a description of the impact on industry and society.

6.1 RESEARCH FINDINGS

The four research questions used for directing the research of this PhD project were presented in section 1.4 of this thesis. The research questions were addressed by seven scientific articles (Article 1 to 7) and in sub-section 5.7.

In the following, the research findings are presented by going through the research questions one by one and providing the answers obtained from the research:

Main RQ1: What are the central challenges construction companies face when gathering requirements and managing them end-to-end?

Answer: The following phenomena that are posing a challenge to construction companies when gathering requirements and managing them end-to-end have been identified:

Obstacles / reasons found during literature searches:

- Gaps between people
- Time to work out a good requirements structure
- Expected effort and time taken
- Requirements effort throughout the life cycle
- Allowance for change and feedback
- Allowance for user's participation and expression of feelings
- Inexperienced clients in requirements management
- Inadequate identification and representation of needs and requirements during the development process
- Unstructured approaches for requirements management
- Misunderstanding and misinterpretation of client needs and requirements
- Communication gaps between participants in requirements management
- Insufficient time to work out a good structure for requirements management
- Inadequate requirements effort throughout the life cycle
- Lack of documentation on changes, and feedback for requirements management
- Lack of users' participation and lack of a voice
- No will to improve
- The construction industry has reached its peak

Obstacles / reasons stated during interviews:

- Lack of knowledge of a requirements management process
- Lack of knowledge concerning systems engineering
- Lack of knowledge concerning the V-model
- Culture / no industry best practice
- Little / no time to handle requirements. Often done by the project manager on the side
- No requirements manager allocated
- No resources
- Lack of training
- No courses / education
- No application of processes in general → Focus on craftsmen and customers instead (mentioned by some of the small companies)
- Short project time
- Little development
- No pressure from customers
- No pressure from competitors
- Sheer number of requirements that have to be managed – lack of overview
- Stakeholders who have to be considered

Obstacles / reasons as a result of data analysis:

- Little discipline of some people in the construction industry
- Unstructured approach (the approach to requirements management was better in Switzerland than in Denmark)
- Lack of planning and risk analysis
- No tool support / .xls at best
- No interest in learning from other fields
- Universities ill-equip their students e.g. M.Sc. students in engineering do not know the V-model
- No real follow-up from industry organizations and government on delays and related cost for society
- No punishment for non-performance

This research has followed a chain of arguments (Figures 1a and 1b) and helped in identifying different sources (categories) of requirements that were relevant to the case project. Both, the way requirements are gathered and handled as well as where requirements originate from, are necessary to identify as this information helps with revealing obstacles and reasons for not making use of structured requirements management.

Based on literature study, interviews, and own experience I arrive at the following conclusions for RQ1: The interviewees at the Danish companies mostly agreed that the way requirements are managed at their company should be improved. Several interviewed persons stated that additional knowledge is needed for managing requirements effectively. Some of the interviewees wondered why there is such little interest from the industry itself, industry organizations, society, and the responsible ministry when it comes to improving the way requirements are managed considering the amount of money there is at stake. At the same time, the interviewees confirmed that the situation has been like this for many years. When I analyze this situation then – after having talked to several industry experts – I arrive at the conclusion that the major obstacle the construction industry in Denmark faces is lack of time and money for improvements such as introducing formal requirements management and educating their staff in it.

This conclusion is not valid for the interviewed Swiss companies. Without exception they had a formalized way for managing requirements in place and stated that their company generally focuses on improving the processes that are used by its employees. They see requirements management as a process.

Having addressed research question one, we can now turn towards research question two.

Main RQ2: How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?

Answer: One proposal for building up a requirements management framework has been made during this research. It consists of 15 building blocks and is shown in Figure 28 below. There are several possibilities for how an effective and efficient requirements management framework could be built up. It is my belief that in essence it is less important how exactly such a requirements management framework is built up (e.g. the order or content of the building blocks could change or building blocks could be added / removed) as long as the identified shortcomings of the construction industry when it comes to managing requirements are covered. Making or using a framework for managing requirements means being aware of the need that requirements *have to* be formally managed on projects and a structured approach *has to* be used for that.

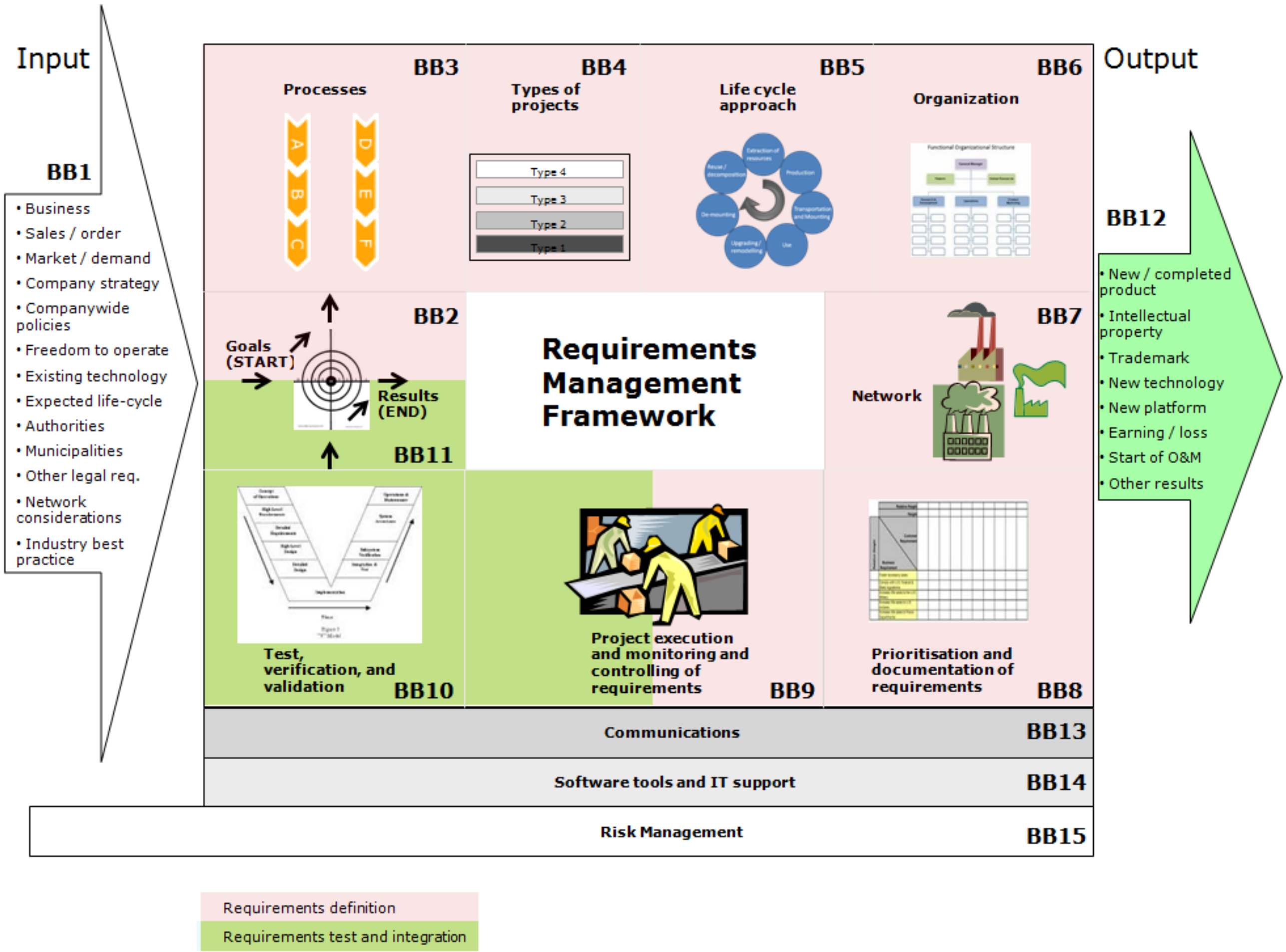

Figure 28 (same as Figure 25, (Wörösch and Mortensen 2014, p. 21)): The identified RMF

When developing the RMF it became very visible why the use of formal requirements management in the construction industry (POL- 1 and POL-2) is essential and what elements of a formal requirements management process are typically missing at construction companies and in existing literature.

A literature review and interviews revealed that there are several elements which are relevant for formal requirements management, that currently are neither incorporated into requirements management frameworks nor the construction industry (neither POL-1 nor POL-2!). Those elements are described in Article 2. The RMF combines best practice from literature and industry.

As the framework has an added life cycle perspective, companies using this framework will find it easier to implement systems engineering at a later stage as big parts of the stakeholder requirements definition process, the verification process, and the validation process based on the INCOSE model (INCOSE 2011) are already being used. It is also my belief that adopting such a framework will help companies to develop and utilize product platforms leading to greater savings and more reliable project delivery.

Main RQ3: How can the developed requirements management framework be implemented and used on the case project?

Answer: The implementation of the RMF on the case project was done by first finding a suitable structure for all requirements as it contributed to quickly getting an overview of the project and its stakeholders. Having such a structure implies that all requirements are documented in *one* place and still are accessible to all key stakeholders. Practitioner's note: It was a struggle to persuade key stakeholders and their IT departments to put their requirements onto another company's server. Doing so also meant educating everybody in the new process and way of thinking so requirements management could be done uniformly.

A member of the case project expressed during one of the interviews: "*All requirements, including financial requirements, are documented at the same place. This makes following up on requirements easier and more operational*".

Once the structure of the requirements was in place the different building blocks of the framework were developed and implemented on the case project at the pace they were needed by the staff of the case project. The function of each building block is explained in Article 2.

A subsequent implementation of the RMF was done on the test house building project. At that point the framework was in a released version as indicated in Figure 4 of this thesis. Even though the framework was not intended to be an implementation model, the implementation of the framework was basically achieved by allocating responsible resources and following the framework itself. Follow-up on the implementation was done at weekly meetings with the project manager. Those meetings were especially important for agreeing on goals as well as grouping and prioritizing the different requirements. At the end of the test house building project it was central to compare the achieved results to the current requirements. The project team had to react to deviations as goals otherwise would not have been achieved or the project would at least have been delayed due to rework. In general involving all stakeholders in due time and continuously communicating with them was important as it guaranteed the most efficient application of the framework.

The RMF was used to determine the goals of both projects and following up on them on a continuous basis. The framework helped to break down main goals into sub-goals and consequently requirements. Those requirements were documented in one place per project to get the total overview of all requirements relevant to the projects. Knowing the total sum of requirements helped in removing duplicate requirements, using synergies of similar requirements by assigning them to the same responsible resource(s), and optimizing the organization of the projects. The use of the framework also helped with finding a solution to contradictory requirements. Once all requirements were implemented the use of the framework made sure that important requirements were verified and validated and that the project team reacted in case of differences between stated requirements and actual results. Having a completely defined scope of the projects was furthermore very helpful for project communications and for managing risks.

Critique: The framework could most likely have been implemented in several ways. The implementation on the case project was “random” as building blocks were developed in the order the project team needed them whereas the implementation on the test house building project was done by following the framework as shown in Figure 28. This means the building blocks were not implemented in the same order. Even though the implementation of the framework was considered a success in both cases the implementation of it can therefore not be 100% compared. As a consequence, vital information that could have been obtained by a 100% comparison could not be acquired and it was therefore not possible to draw any conclusions on that.

A major learning point is that there should be a dedicated person for implementing the framework. This will ensure a faster implementation and somebody to take care of the project team’s concerns and complaints (a new, major process is being implemented and used after all).

Another key learning point is that aligning project requirements to business strategies and requirements is fundamental. It contributes to improving the bottom line of a company and guarantees the support of senior management.

In short: The implementation of the RMF was successful (the framework could be fully implemented by the allocated project staff in due time and on budget) and its use did not cause problems other than spending time on a new process and all that comes with the implementation and use of major processes in general.

Supporting RQ4: How can the effectiveness and generalizability of the requirements management framework be demonstrated and how can they be validated?

Answer: The effectiveness and generalizability of the requirements management framework were demonstrated by the results of the expert peer reviews (section 5.7.3) and the implementation of the framework on the case project and test house building project. The validation of the effectiveness and generalizability of the requirements management framework was done by applying different kinds of validation and looking at the results / conclusion:

- The framework was applied to extreme conditions (building project, technology development project, product development project, and product platform development project in parallel) on the case project, with the conclusion that the framework works under those conditions
- The successful application of the framework to the test house building project. As recommended by Mishler (1990) the quantitative validation of the framework that was done was very limited. Instead a qualitative analysis of the framework in its entirety and a qualitative analysis of each individual building block of the framework were instigated with encouraging results. The most encouraging result was that two of the Danish companies and

one authority, consisting of academics and practitioners, already asked for the implementation of the framework. This was a strong validation

- A comparison of the test house building project's performance on time and money was done on two of the case company's previous building projects of similar size. The result of this comparison was that the test house building project – that used the RMF – had a better performance on the parameters time and money than the two projects it was compared to
- Face validity gave a confirmation that the framework as such is effective on projects sizing from 100 m^2 to 200.000 m^2 or 13.400 M€ to 670 M€ respectively
- Expert peer reviews conducted in Denmark and Switzerland established that the framework is grounded in reality and addresses the requirements management-related challenges that the reviewers encountered in their work. Moreover the framework is not limited to mainly focusing on customer requirements but has an end-to-end approach covering the whole life cycle of a building in terms of requirements
- "*Traces*: The behavior of specific variables is traced through the model and through simulations to determine if the behavior is correct and if necessary accuracy is obtained" (Rykiel 1996, p. 236) and "Multistage validation: Validation methods are applied to critical stages in the model building process: (1) design: Develop the model's assumptions based on theory, observations, general knowledge, and intuition; (2) implementation: Empirically test the model's assumptions where possible; and (3) operation: Compare the input-output relationships of the model (compare theory and output, of a test house for example) and the real system" (Rykiel 1996, p. 236). Table 4 shows a mapping of the executed validation of the framework to defined validation procedures
- A theoretical application of the framework to a street tunnel building project as described in Article 7 was done to find the boundaries of its application. It turned out that the framework could be applied to this kind of building project as well

Table 4: A mapping of the executed validation of the framework to defined validation procedures (Wörösch and Mortensen 2014, p. 8)

		Performed validation			
		Theoretical validation	Expert peer reviews	Expert peer reviews abroad	Building project
Validation procedures as described by Rykiel	Traces	X			
	Extreme-condition tests	X	X	X	X
	Face validity		X	X	X
	Multistage validation	X			X

When re-visiting the 9 associated problems of requirements management in construction from the literature review as Yu and Shen (2013, p. 225-226) presented, it is estimated by me that the framework directly addresses 6 of those problems. The remaining three problems are supported by the framework; however, the ‘experience level of clients in requirements management’ and ‘the inadequate requirements effort throughout the life cycle’ cannot be controlled by the framework but only supported by providing a useful structure and a number of recommendations.

6.2 ACHIEVEMENT OF GOALS

In section 1.3 the goals of this PhD project were presented.

Let us revisit the goals and evaluate them one by one:

Research goals:

- **Fill the gap of not applying formal requirements management to the construction industry (POL-2) by providing a generic process for managing requirements:** The RMF was developed and is ready for employment on a conceptual level in POL-2. The results of the implementation of the framework in POL-2 as well as interviews conducted with POL-1 companies lead me to the conclusion that the framework most likely can be applied in POL-1 as well. No data was found that advises against it
    a) **This process is targeted to be a generic framework for managing requirements in the construction industry that can be used by many project and requirements managers:** The RMF is of a generic nature. Face validity confirmed that this framework can – at least in theory – be applied to all building projects that have been examined so far
    b) **The INCOSE systems engineering handbook (INCOSE 2011) and PMBOK (PMBOK guide 2013) will be used as a base for the generic framework as those standards are successfully being applied for managing requirements in other industries. This is a goal and pre-requisite at the same time:** The RMF builds upon both standards
- **Provide evidence to support the claim that formal requirements management successfully can be used in the construction industry:** Using requirements management worked for the case company and expert peer interviews indicate that it will work for projects in other construction companies (at least in Denmark and Switzerland) as well

Goals related to the case project:

- **Help the case project to manage the different requirements that have to be handled when running a series of building projects:** This was achieved by means of a requirements structure, the RMF, and The product requirements development model
- **Build a model that can help with quantifying the impact of new and changing requirements for an existing product architecture. This model is described in Article 4:** The product requirements development model was developed and is ready for utilization
- **The RMF is targeted at single family houses of up to two floors, large housing, and office buildings of up to 200,000 m^2.** This goal was achieved by means of face validity and the test house building project

Other goals:

- **Initiate the moving of an entire field of business:** This has been started. The first companies have asked about the implementation of the RMF. Other companies were interested in the test house and how it was handled process-wise. A seed has been planted...
- **“Check the religion” of your research department. Members of my research department have continuously been advising construction companies to base their products on product platforms as described by Meyer and Lehnerd (2011), to use clearly described product architectures (Ulrich 1995, Vezzetti et al. 2011), and apply the concept of mass customization (Pine 1999) where possible. Performing this “check” on the case project will provide further data to my research department:** This goal was only partly achieved. I have now a much better understanding of the research within my department. I also think the research done at my department is of high quality, relevant, and useful. But as my focus typically is on the entire life cycle I have to say that more phases have to be covered than design and development for being even more helpful to my research. An interesting observation is that my research department currently undergoes a change away from qualitative research towards more quantitative research. Therefore, it is my perception that if I had to initiate this very PhD project today, I would not get the permission to start as my research is qualitative in nature

I am satisfied with the achievement of the goals that have been defined at the beginning of this research project.

6.3 CORE CONTRIBUTIONS

By introducing the RMF this research has to my knowledge – for the first time – shown that formal requirements management and elements of systems engineering can be implemented in the field of construction.

Therefore the core contributions of this research are:

- A requirements structure
- The introduction of formal requirements management and elements of systems engineering to the field of construction (POL-2 and most likely POL-1)
- The RMF that considers aspects that currently are not considered in the construction industry:
    a) The life cycle of a building (I am aware of the fact that BIM and facility (or facilities) management (e.g. Payne 2012) to some degree do have life cycle considerations. But the use of both is not widespread in Denmark, yet)
    b) Test, verification, and validation of requirements
    c) Project result analysis
    d) Different types of projects that are run parallel to building projects
    e) The network of a company
- The product requirements development model

I am satisfied with the obtained core contributions of this research project.

6.4 INDUSTRIAL IMPACT

6.4.1 THE INDUSTRIAL IMPACT OF THIS RESEARCH

The research described in this thesis shows for the first time the application of elements of systems engineering and formal requirements management on projects in the construction industry. Applying such a structured approach improved the case project's and test house project's ability to deliver in time and on budget. It was also felt by customers and by the project team that the quality of the delivered items was high. Those benefits were expected to materialize as the use of systems engineering had contributed positively to other fields of engineering (Elm et al. 2008 and Frederick and Sauser 2007) before. Please note that more information on how this research impacted the case company by being better at managing requirements can be found in Articles 2 and 7.

The results of this research were communicated to interested readers in the form of articles, presentations at conferences, and this thesis. Furthermore, the test house and some of the data gathered while producing and building it were shown to a public audience. Now it is up to other construction companies to look at this example, evaluate the data, and judge for themselves if they think they will benefit from adopting such an approach.

What was already achieved is that some companies started evaluating the RMF and asked for further descriptions or an implementation of it.

If more construction companies start focusing on a structured approach towards requirements management and perhaps even the use of systems engineering one would expect better project planning, fewer project delays and more throughput, more deliveries within budget, considerations of the whole life cycle of a building when taking project decisions and thereby less maintenance, and more satisfied customers. This increased focus on formal requirements management will force construction companies into new ways of working as attention has to be paid to the use of processes and the support of databases. But the gain of doing so will most likely be higher profit margins than the ones that currently can be seen.

6.4.2 THE INDUSTRIAL IMPACT OF THE CASE COMPANY AND ITS PRODUCTS

This research contributed to something bigger. Something that involved a lot of time, money, and people:

A new kind of HPC material that is aesthetic, slim, able to withstand fire, and reduce CO_2 emission during production, transportation, and use was invented.

In addition new ways of producing HPC material, new jointing solutions that can last as long as a building without having to be replaced during use, short mounting times of HPC sandwich panels, and new dimensions of sandwich panels were created and tested at their boundaries.

This new knowledge and patents will be used to push competitors and will therefore have a significant impact on certain parts of the construction industry.

6.5 IMPACT ON SOCIETY

6.5.1 HOW THIS RESEARCH IS EXPECTED TO IMPACT SOCIETY

If construction companies start using a more structured approach to requirements management, e.g. by using the RMF, than they currently do this is expected to have a positive influence on society as the price of houses and buildings could be decreased and / or the profit rate of construction companies could be increased. This in return would mean that fewer construction companies go bankrupt, more employees can be retained, and more houses can be sold as more people can afford them.

As for the Danish market: Cheaper houses help to keep foreign competitors away. Currently a rule of thumb seems to be that building the same house costs 100% in Germany, 120% in Sweden, and 140% in Denmark (Jespersen 2012). This means that e.g. German companies can enter the Danish market by offering houses at lower prices even though taxes are higher in Denmark. This is already happening in the Copenhagen area.

Using formal requirements management is also expected to have a positive impact on the quality of buildings. This helps with saving a lot of money for society as it means less rework and thereby increases the amount of projects that can be completed per year. Such a positive trend could strengthen Denmark's financial position in the global competition.

6.5.2 THE EXPECTED IMPACT OF THE CASE COMPANY AND ITS PRODUCTS ON SOCIETY

The case company and its products can play a key role in the industry and society for many years to come.

They make a product that helps to reduce the emission of CO_2 considerably. As 5% of the world's CO_2 emission is caused by the construction industry this is a big achievement.

Their buildings have thin walls that already live up to the 2020 (and the expected 2025) requirements for saving energy. Those requirements are issued by the European Union (European Union press release 2008 and European Union 2010). Having thin walls means an additional 12 m^2 per floor of a standard single family house in addition to more light coming into it compared to the traditional way of building and insulating houses.

The case company demonstrated that 40 m^2 buildings for townships can be produced and built for less than 5000 € per unit. This can have a huge impact on refugee camps. Haiti was mentioned as an example. Cooperation with organizations aiding refugees is obvious.

A powerful idea is the mobile factory (patent pending). It enables the casting of concrete elements on-site. This means that even far out on the country side, where infrastructure is scarce, houses can be built using local labor and material.

As to the facade of buildings the case company has achieved two things:

1) The facade can be personalized (color, letters, surface). This has potential to change the look of settlements notably
2) When insulating already existing buildings the inhabitants do not have to move out anymore. Not even for removing the old windows and putting in new ones. That saves building owners a lot of money and inhabitants the trouble of temporarily moving out

7 SUGGESTIONS FOR FURTHER RESEARCH

A lot has been achieved during the past three years. But there are limits to what one person can accomplish. Therefore there are still many areas left that should be researched further. Those areas have been divided into *general areas for future research* and *future research related to this research project*:

General areas for future research: A series of observations that were made during the past three years leads to the impression that the construction industry is under-researched. Those observations (and suggestions for the related future research) were:

- The construction industry has only improved its labor productivity by factor four in a period of 40 years (Kristensen 2011, p. 110). What can be done to improve this number? Apart from using requirements management many factors such as the use of robots and machinery, resource simulators, better planning and risk management and organizational improvements can contribute to improve this number
- Only a few percent of construction companies are engaged in Research and Development (R&D) activities. The official number for Queensland, Australia is one percent. For Denmark no official numbers exist. What is measured in Denmark instead is product innovation. According to Statistics Denmark (2011) eight percent of the Danish construction companies have reported to be innovative on products. Note: Being innovative is not the same as doing structured research and development. Even though eight percent is much higher than one percent both numbers are still too low for an industry to be able to evolve at a satisfactory pace. How can more construction companies be persuaded to engage in R&D activities and thereby move the field and society forward? I am aware of the discussion of how to determine the actual amount of money that is spent on R&D. Laborde and Sanvido (1994) state that the construction industry only spends 0.4 percent of its annual output on R&D. Brockmann and Brezinski (2014) doubt that number and propose a different way of calculating the amount of money that is spent on R&D per year. They arrive at 12-15 percent R&D spending per year
- Systems engineering is not being used in construction. The use of systems engineering in construction should be researched further
- Many more construction companies could build their products (buildings as well as parts of buildings such as bathrooms, staircases) based on product platforms. Research is needed proposing product platforms in construction that construction companies perceive as beneficial. The mind-set of mass customization, where the low unit costs of mass production are combined with the flexibility of individual customization, might be applicable here
- Formal requirements management has not found its way into construction, yet. More research is needed facilitating that
- When building something new (something that a particular company has not built before) one third of the time spend on the construction site is idle time. Interviewees stated that the situation has been like this for many years. Even though simulators for the efficient use of

teams and material on building sites already exist, their use is still very limited. It has to be examined how the on-site idle time can be decreased and how the existence of simulators can be communicated to construction companies

- Construction is still known for: Not delivering projects within budgets, late deliveries of projects, not considering project decisions from a "whole life cycle perspective", and poor customer satisfaction (Fernie et al. 2003, p. 355). Research is needed to follow the development in those areas and to see if this statement is true for the construction industry as a whole
- Knowledge sharing in construction could be improved significantly. Knowledge is often not shared due to a construction company´s later liability for the disclosed information as is the case with BIM. BIM was first described by Nederveen and Tolman in 1992. When working on a new project it is also not customary (this was confirmed during interviews) to approach other companies or forums to exchange information. How can knowledge sharing in construction be improved?
- There is a great need for decent, cheap, and long lasting housing for township dwellers. Even though this has been the case for many decades the construction industry first now has started finding solutions to this problem that are economical. What can be done to decrease the price of long lasting housing for townships further?
- Residential and commercial buildings are responsible for about 40% of the total energy consumption and 36% of the total CO_2 emission in the European Union (European Union 2008). This number has been too high for too many years. More research is needed to see how this number can be decreased significantly

The above points are of a general nature but give a clear indication of an under-researched industry. It is therefore recommended to do (further) research on those topics.

Future research related to *this* research project: Answering the main RQ's has pointed towards additional, interesting research projects that could be investigated in the future. In the following section each of the RQs are followed by a description of interesting research projects to perform:

Main RQ1: What are the central challenges construction companies face when gathering requirements and managing them end-to-end?

A larger number of companies would have to be interviewed for the challenges they see when it comes to using formal requirements management to get a more complete picture of the industry (POL-1 and POL-2). The overview given in section 5.7.2 is not exhaustive.

Also, the Danish construction industry should be compared to the construction industries of other countries. The comparison of the interviewed Danish construction companies to the ones in Zurich, Switzerland has already revealed some major differences. More dissimilarity is expected to surface when interviewing construction companies in additional countries. Those differences have to be analyzed as they are major learning points that can help in spreading the use of formal requirements management – not only in Denmark.

Main RQ2: How should a requirements management framework be built up in order to counteract the requirements management-related challenges that construction companies face?

The RMF was built upon the following concepts: Formal requirements management – including a structure for handling requirements – and systems engineering as well as product development, product platforms, modularization, and product architecture. As those concepts are vast, more research is needed to guarantee the optimal build-up of the framework:

- Do additional concepts have to be applied? Are there areas that could contribute to the framework that have been overlooked? This would most likely result in further building blocks being added to the framework
- Where are the boundaries of the RMF? Is there a maximum size of a project that the framework successfully can be applied to? The framework was – at least in theory – successfully applied to tunnel projects. Are there other types of construction projects the framework can be applied to?
- An examination of a time related dimension of the framework is required. What works today might not work in 20 years from now
- The prescriptive approaches (read "operational check lists") for the project / requirements manager for each building block and project phase have to be developed and tested. This moves the framework from being on a conceptual level to a fully operational level
- Investors and construction companies offering a fixed price for maintenance (as can be seen in Germany) might be interested in probability calculations of future events in order to have a realistic picture of a building's life cycle cost. If that is desired more research is needed. This

thesis covers a structure for handling requirements that tries to anticipate possible future events

- A supporting model – The product requirements development model – for quantifying the impact of new / updated requirements on an already existing product architecture was made and described in Article 4. In relation to the supporting model it would for instance be interesting to investigate how matrix-based analysis methods, such as partitioning (Gebala and Eppinger 1991, Kusiak and Wang 1993), could be solved with the Variant-DSMs and DMMs of the model. Here, future research can for instance focus on what impact structural improvement of the product, through modularization for example, could have on the entire product architecture as well as on new requirements

Apart from that, The product requirements development model has to be applied to further cases. The hypothesis is that it can be applied to all fields and its use is not limited to construction.

Additionally – as part of looking into product architecture and PLM systems – it was investigated how using a visual product architecture representation in combination with a PLM system to support the development activities of modular designs can be described. The results from the study encompass new PLM capabilities for handling multiple product structures, visualising multiple architectural views on products, controlling interfaces, and quantifying and communicating the status and progress of product-related resources. Because this work is still in its early stages the following items were identified for future research:

- First, more experience from applying the approach has to be gathered, in order to estimate the value of using it. The aspects to investigate should cover the approach's usability, its applicability, and its usefulness. Such studies could compare product families within and across industries, and link them to performance measures of interest i.e. development time, cost, revenues, quality, etc.
- Second, the study of the application effects of the approach over time should be done. Successive generations of a product family supported by the PLM approach could be described and measured to investigate the aspects of architecture evolution
- Third, detailing of the version and revisions to the control of structures should be performed — in order to support engineering change management in a more structured way

Main RQ3: How can the developed requirements management framework be implemented and used on the case project?

What is left for future research in relation to RQ3 is:

- The utilization of (especially designed) tools and databases supporting the use of formal requirements management in the construction industry has to be examined. This can be tested on the case project and then rolled out to other parts of the construction industry
- Training of key personnel in formal requirements management is needed. A whole field needs to be educated in the practical application of formal requirements management. How can training of a whole field be done in an efficient way? Experiences from the case project can be used as a starting point
- Is the project management model used in the case project the best choice when working with the new requirements structure and the different life cycles?

Supporting RQ4: How can the effectiveness and generalizability of the requirements management framework be demonstrated and how can they be validated?

The RMF has performed well on the case project and on the test house building project. Additionally expert peer interviews were conducted. So far results indicate that the framework is usable, applicable, useful, and efficient. Nevertheless more research is needed:

- When is a construction project large enough in size to economically justify the use of the RMF? So far this research indicates that for construction projects above €10M the use of the framework is beneficial and therefore justified. But is this number still correct when many more construction companies are interviewed?
- When is a construction project too large for applying the RMF?
- The framework has to be applied to further building projects in order to gather more data. Comparing those data to previous, similar building projects will show the effectiveness of the framework. If the framework can be applied to other building projects without great modifications this will help to prove its generalizability
- How does introducing structured requirements management to the construction industry impact this industry, its customers, and society in the long run? Do profit margins increase? Are more jobs created? Are houses getting cheaper? Is the number of projects being delivered in time and on budget increasing?

8 CONCLUDING REMARKS

The past three years have been an amazing period for me. For many years I have nourished the wish to immerse in an engineering “problem”. This wish became very strong in my last two positions as a manager where there was very little time to look into any of the issues the engineers reporting to me had the pleasure working with. Therefore, when Professor Lars Hvam, DTU, called to offer me a PhD project, I was not in doubt and jumped directly into it. I have not regretted this change for a single day – even though I, at times, have been missing having a personal assistant.

It was great learning about an industry from so many different angles and being able to help at least the staff of my case project (and anybody else who wants to use my work). Many of the people I have met left a lasting impression on me. This, together with the fact that I went from a really nice salary to the salary and prestige of a “mere” PhD student (even though PhD students are often smart people I could sometimes feel a difference on the negative side in the way some people have been treating me when I approached them as a PhD student. Those people would not treat a manager in the same way), gave food for thought and has definitely changed me as a person.

But enough about me! I hope you deem this PhD thesis useful and found reading it as interesting as it was for me writing it.

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10 APPENDICES

Appendix 1:

"Questionnaire that was used to gather stakeholder requirements – project team version"

Appendix 2:

"Questionnaire that was used to gather stakeholder requirements – company version"

Appendix 3:

"Questionnaire that was used to validate the requirements management framework"

Appendix 4:

"CIB poster presentation (The only poster presentation of this PhD project)"

Appendix 5:

Short curriculum vitae of the author

APPENDIX 1 QUESTIONNAIRE – PROJECT TEAM VERSION

Questionnaire used for requirements gathering – project team version

1. Explain the background of this interview / questionnaire.
2. *Walk through the requirements management xls.-file together.*
3. How important is the price of the system?
4. What kind of system requirements are there?
5. What are the dependencies between the project's stakeholders?
6. Which requirements are there from your business unit?
7. What kind of requirements are there for the elements (physical requirements)?
8. What kind of requirements are there for the jointing (physical requirements)?
9. What kind of tolerance requirements are there?
10. Are there any authority requirements relevant for your area?
11. Are there any general authority requirements that you know of?
12. Are there any requirements for production?
13. Under what conditions do we produce?
14. Are there any process related requirements?
15. What kind of requirements are there for product development?
16. What kind of requirements are there for test and verification (often related to authority requirements)?
17. How are acceptance criteria defined?
18. Are there any requirements that are relevant to the customers?
19. What requirements do you have to the project manager?
20. Do you have any personal requirements for the project?
21. Please name the ”priority 1” requirements.
22. Are there any requirements for transportation?
23. Are there any requirements for assembly? E.g. one universal tool for everything we assemble.
24. Are there any requirements concerning the precision of measurements? Are there requirements for using a laser for measuring of points?
25. Are there any requirements for the decomposition of elements?
26. Are there any requirements related to the traceability of elements (e.g. eco certified)?

27. Is there anything we can make modular (modularization requirements; dimensions, module size)?
28. *Sort the requirements by life cycle phase → Show the life cycle! (Figure 4 in article 1)*
29. Do you have any recommendations for improving this questionnaire?
30. Please make your own list of requirements for your area and send it to me.
31. Additional question: Do you think that the process of handling requirements needs improvement?

APPENDIX 2 QUESTIONNAIRE – COMPANY VERSION

Questionnaire used for requirements gathering – company version

1. Background of this questionnaire (oral explanation).
2. How many employees are working at this company?
3. What is the size of this company's projects in m^2 and in the local currency?
4. What kinds of projects are being run in this company apart from construction projects?
5. Please describe the processes you use in construction?
6. How does your company's requirements gathering and –management process look like today?
7. Are all requirements of a construction project documented at ONE place? If yes, where?
8. Do you work with life cycles?
    - If yes, are requirements assigned to different life cycle phases?
9. Does your company work with other processes that need to be considered in construction projects?
10. Are you using requirements management in construction projects?
    - Do you have a requirements manager?
11. What are the most important parameters when building a house: price, quality, reputation, keeping time schedules, …?
12. Does your company have a defined system?
    - If yes, what (system) requirements are there to that system?
13. Do you work with product platforms?
14. Do you work with modularization?
15. What are the typical stakeholders of your projects?
16. What are the dependencies between you and your stakeholders?
17. What are the most important requirements for your customers?
18. Do you use sub-suppliers?
    - If yes, what requirements do you have towards the sub-suppliers?
19. What requirements are there for the project management?
20. Are there requirements from other business units that need to be considered?
21. Are there any personal requirements that need to be considered in construction projects? E.g. appraisal talks.

22. What kinds of requirements are there from authorities?
23. Are there requirements for the development of your products?
24. What kind of requirement is there concerning test / verification? (often connected to authority requirements).
25. How are the acceptance criteria defined?
26. Does your company develop material?
27. Does your company develop technology?
28. Do you work with pre-fabricated elements?
    - If yes:
        i. What are the requirements for the elements (physical requirements)?
        ii. What are the requirements for the jointings (physical requirements)?
29. What tolerances are you working according to?
30. Are there any requirements for production?
31. Under what conditions does your company produce?
32. What are the three most important requirements in your construction projects?
33. Are there any requirements for transportation?
34. Are there any requirements for the assembly of a building? E.g. one tool for everything.
35. When measuring: Are there any requirements concerning measuring precision? Are there requirements to use a laser for measuring?
36. Are there any requirements for the decomposition of elements?
37. Are there any requirements for the traceability of material (E.g. eco label)?
38. Are you working with any type of requirements that we haven't been talking about when going through this questionnaire?
39. Do you have any recommendations that could improve this questionnaire?
40. Additional question: Do you think that the process of handling requirements needs improvement?

APPENDIX 3 QUESTIONNAIRE – FRAMEWORK

Interview questions to the requirements management framework

1. Explain the framework! (The background of the framework is explained during the interview).

2. What is the interviewees' opinion about the framework? What is the interviewees' immediate impression?

3. Is the framework based on reality?

4. Is the framework useful?

5. Where, who, when and in what situations (cases) can the framework be applied?

6. Is the framework operational? If no, what is missing?

7. What is good about the framework and what should be improved?

8. Would the interviewee use the framework him / herself? Why? Why not?

9. Has the interviewee earlier encountered similar frameworks?

10. Additional question: Is there a need for a requirements management framework (end-to-end process)?

11. Additional question: Does the framework solve your requirements management related issues? Fully? To a large extend? Somewhat? Not at all?

APPENDIX 4 POSTER PRESENTATION

Product platform considerations on a project that develops sustainable low-cost housing for townships

Problem description

It is estimated that about 1.6 billion people around the world live in sub-standard housing and over 100 million are homeless. If no serious action is taken the number of slum dwellers is expected to rise from one billion people today to two billion within the next 30 years (Habitat for Humanity, 2013). This leaves many developing countries with a problem that is hard for them to overcome.

What and how?

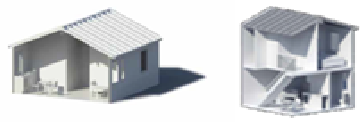
The case company described in this article examined whether and how it would be possible to contribute to the housing problem of developing nations with its knowledge and technology. After a careful examination of the National Housing code (South Africa), the decision was taken to develop a low-cost product platform. The case company already had two other product platforms at that time. Action Research on a case project has been chosen as the research approach.

Goals

Build 40 m2 stand-alone houses that are based on the low-cost product platform and made from High Performance Concrete (HPC) sandwich panels at a price lower than 55.706 ZAR (= **4.927 €** using exchange rates from December 25th 2012) per house.

Modularity of the houses based on the low-cost product platform has to be ensured.

The produced buildings must be sustainable.



Two different 40 m2 houses made from HPC – Type 1 and Type 2

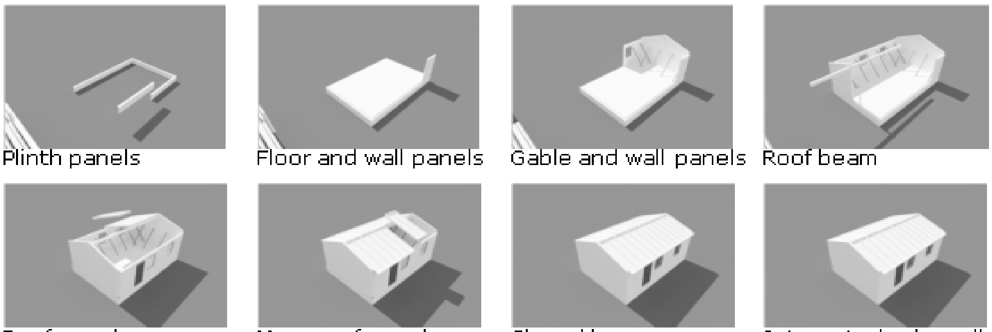
Results

The low-cost product platform currently supports three types of houses. Two of them are shown above. Modularity has been achieved on two levels: Element level and building level.

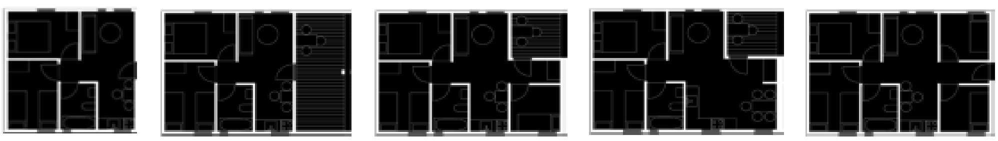
The target price has been achieved.

A Type 1 house can be erected within **8 hours** once the foundation is in place.

The product platform approach is a valid strategy for meeting the low cost housing demand of developing countries.



A Type 1 house assembled from prefabricated HPC elements



The five variants of a Type 1 house

Michael Wörösch

M.Sc., M.Eng., PhD student
Department of Mechanical Engineering
The Technical University of Denmark, DTU
Phone: +45 27 11 41 42
E-mail: mwch@mek.dtu.dk
Authors: Michael Wörösch, PhD student; Martin Bonev, PhD student; Niels Henrik Mortensen, Professor

APPENDIX 5 CURRICULUM VITAE OF THE AUTHOR

Curriculum vitae of the author

EDUCATION

PhD – Expected end of study on February 28th 2014

PMP – PMI Certified project manager

EBA (Engineering Business Administration; Part time study; Bachelor's degree)

Mechanical Engineer (Main study in Germany, practical term in Israel, and final thesis in Denmark)

Industrial Mechanic

EMPLOYMENT HISTORY

2011 – DTU Department of Mechanical Engineering, Kgs. Lyngby

Position: PhD student

Main focus: Researching the use of requirements management in the construction industry. Teaching in systems engineering, product platform development, and modularization

Results: Two new conceptual models, insight into the Danish construction industry, seven articles

2009 – 2011 BaneDanmark, Østerbro

Position: Head of Program Management Office

Main responsibilities: Finance and planning, risk management, contract management, asset management, program strategies according to PRINCE2 and MSP, quality management and ISO certification, IT related infrastructure (e.g. Sharepoint, ProArc), work environment, and minor projects

Results: Building up a PMO from scratch, financial control without remarks of an 18 (+6) Billion DKK program

2007 – 2009 Dako A/S, Glostrup

Position: Director, software development

Main responsibilities: Development of a software platform to control medical devices based on a Service Oriented Architecture (SOA), interface management, software test, due diligence and integration into Dako

Results: Building up a complete software organization from scratch (team, offices, processes, tools, …), many ideas for patents, strategies, reduced maintenance effort, FDA approved documentation

2006 – 2007 connector A/S, Skovlunde

Position: Consultant

Main responsibilities: Teaching project- and program managers, selling courses

Results: Certified managers and sold courses

2006 – 2006 Ementor A/S, Ballerup

Position: Project Manager

Main responsibilities: Module development of a document handling system, business development

Main results: Delivered modules, successful bidding on tenders

2002 – 2004 Flextronics Denmark A/S (Former Microcell Denmark A/S), Copenhagen SV

Positions: Program Manager and R&D Manager

Responsibilities: Development of a new platform for mobile phones, development of a mobile phone, and production of first batch using a platform from Ericsson Mobile Platforms

Main results: Successful hiring of specialists, mobile phones and production of first batch (5,000 phones)

2001 – 2002 & 2004 – 2005 L.M. Ericsson A/S, Copenhagen SV and Lund

Positions: Project Manager and Senior Project Manager

Responsibilities: Merging of software platforms, development of call centers

Results: Saving a 80,000 man-hour project that was in serious time problems, a call center for 15,000 callers

1996 – 2001 GN Nettest, Brøndby

Positions: Development Engineer, Section Manager / Project Manager, Product Manager

Responsibilities: Development of a software platform and compilers

Results: Working product platform based on software, hardware, and mechanics, a sellable surveillance system, successful negotiations and start-up of outsourcing activities, CMM level 3

COURSES AND CONFERENCES

Courses and conferences have been attended in the following vicinities: Management, economy, communications, LEAN, safety at work, telecommunications, programming, project management, engineering design, mechanical engineering, QRS and design control for medical devices

LANGUAGES

I speak and write German (mother tongue), Danish, and English fluently.

PERSONAL CHARACTERISTICS

I would describe myself as: Result oriented, structured, responsible, decisive, and motivating

SPARE TIME INTERESTS

After a hard day's work I enjoy being together with my family and our pets. I like playing computer games and reading books. When time allows it I am together with friends or active at the parentteacher association at my son's school.

11 APPENDED ARTICLES

Article 1:
Structuring Requirements in a Multi-Project Environment in the Construction Industry: A Life Cycle Perspective

Status: Published in the proceedings of the ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, (ASME IDETC/CIE 2012), Chicago, Illinois, USA, August 2012

Article 2:
A Requirements Management Framework for Construction Companies Offering Pre-defined Products

Status: Submitted to the "Journal of Construction Management and Economics"

Article 3:
Product Platform Considerations on a Project that Develops Sustainable Low-cost Housing for Townships

Status: Published in the proceedings of the CIB World Building Congress, Brisbane, Australia, May 2013

Article 4:
Extending Product Modelling Methods for Integrated Product Development

Status: Published in the proceedings of the ICED 13, Seoul, South Korea, August 2013

Article 5:
Product Data Management for Supporting Modularisation in Product Family Development

Status: Accepted with minor revisions by the ISI indexed Journal "Computers in Industry"

Article 6:
Utilizing Product Platforms in Industrialized Construction

Status: Submitted to the "Journal of Construction Management and Economics"

Article 7:
Validation of the Requirements Management Framework for Construction Companies Offering Pre-defined Products

Status: Ready and peer reviewed at the department. This is a follow-up article to Article 2. It will be submitted to the "Journal of Construction Management and Economics" once Article 2 is accepted

ARTICLE 1 STRUCTURING REQUIREMENTS

Structuring Requirements in a Multi-Project Environment in the Construction Industry: A Life Cycle Perspective

Published in the proceedings of the ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, (ASME IDETC/CIE 2012), Chicago, Illinois, USA, August 2012

Proceedings of the ASME 2012 International Design Engineering Technical Conferences (IDETC) and Computers and Information in Engineering Conference (CIE)

IDETC/CIE 2012

August 12-15, 2012, Chicago, Illinois, USA

DETC2012-70860

STRUCTURING REQUIREMENTS IN A MULTI-PROJECT ENVIRONMENT IN THE CONSTRUCTION INDUSTRY – A LIFE CYCLE PERSPECTIVE

Michael Wörösch
Technical University of Denmark
Lyngby, Denmark

1. ABSTRACT

Being in control of requirements in building projects is vital, since it helps securing the often small profit margins and the reputation of the responsible company. Hence this research aims to introduce requirements management to the construction industry. By means of case study and action research conducted at a Danish construction syndicate producing sandwich elements made from High Performance Concrete and insulation materials it is demonstrated that requirements management successfully can be used in construction. Since requirements management as of today has not found its use in this industry, yet, success is here defined as an accomplished and accepted implementation of requirements management processes that are used by the relevant project members in their daily work and where the benefits of implementing requirements management outweighs the cost of invested resources. Furthermore it is argued that when running technology development, product development, product platform development, and a portfolio of building projects at the same time the use of requirements management is advantageous and an intelligent way of structuring requirements is needed. This article also demonstrates that the application of requirements management with gain can be extended to cover entire life cycles as e.g. the life cycle of a building. This is done by proposing a requirements structure that attempts to consider future events. The proposed structure is divided into the areas: company, technology, product platform, and building and covers all encountered types of requirements, e.g. functional (defines what a system is supposed to do), non-functional (defines how a system is supposed to be), technical, organizational, and even personal requirements. As a result the conducted research clearly shows that requirements management can be applied to the construction industry. At the same time it also becomes obvious that it is necessary to open doors to further research looking into not only using requirements databases & processes especially designed for the construction industry but also the training of key personnel in requirements management, and how the introduction of requirements management can impact the construction industry and their customers in the long run.

2. INTRODUCTION AND PROBLEM

According to EU, 2010, residential and commercial buildings are responsible for about 40% of the total energy consumption and 36% of the total CO_2 emission in the European Union [1]. Therefore, ambitious targets for lowering the energy consumption of new buildings and energy renovation of existing buildings are being implemented in the national and European policies, and by the year 2020 nearly zero energy buildings will become a requirement in the European Union. As a result, energy performance has become an important issue in the design of new buildings and in the renovation of existing buildings. It is expected that over the next 20 years around 40 % of all buildings need to be re-insulated. It is also expected that the requirements for saving energy that are valid in 2020 will gradually be made more rigid in the decades to follow as this has been a clear tendency up till now [2]. In this article many other examples of an ever increasing complexity that needs to be handled when running building projects will be given. In order to be able to handle this complexity and at the same time to save cost, minimize schedule delay and risk in general it is necessary to introduce requirements management to the construction industry.

In accordance with DS/EN 206-1 the lifespan of a concrete house is at least 50 years [3] and, as said by a Swedish report, the lifespan of a brick house is often more than 100 years [4]. During those years the house will be met with a lot of new requirements in respect to its size, shape, and the use of new technology.

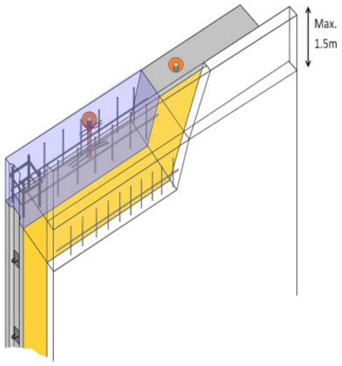
Therefore it makes sense to apply requirements management not only to building projects but also to the entire life cycle of buildings. Consequently, this means that a desired requirements structure has to be able to cover a lifespan of up to a hundred years and needs at the same time to be compatible to future demands, since a continuously updated requirements structure can contribute to e.g. product content documentation or calculating the life cycle cost of a construction as often requested by investors.

Problem:

The key issues and questions this article wants to give an answer to are: (1) is it practically possible and beneficial to apply requirements management to the construction industry and thereby building projects, (2) can requirements management be applied to the entire life cycle of a building and not only until the end of a building project, (3) and, if so, can the structuring of the requirements be done in a feasible way that tries to take future events into account. (1) to (3) will be illuminated in the framework of a multi-project environment as technology development, product development, product platform development and running two building projects at the same time has been a reality in the case project examined in this article.

Examples of trade-offs in the requirements structure that have been found on different levels [5, 6], will also be given.

This article is based on a case study [7] and action research [8], [9] conducted at a Danish construction syndicate. Its members established a case company called “Connovate” [10] that produces low energy buildings and insulation panels of pre-fabricated High Performance Concrete (HPC) sandwich elements. Figures 1 and 2 show examples of HPC sandwich elements.



Figures 1 and 2 – A drawing and a real life picture of a HPC sandwich element

In order to live up to the European Union's requirements as well as the need for modularity, this syndicate has chosen a cradle to cradle strategy for improving many of the relevant parameters [11], as e.g. a low consumption of raw materials, a low emission of CO_2 of the finished HPC sandwich elements, no use of harmful chemicals, a rational production and assembly process, a pre-fabrication design that supports modularity, and an energy optimized way of transporting the pre-fabricated HPC sandwich elements, on a running basis. This would enable the syndicate to be a building owner's sole supplier during the entire lifetime of a building. To have a clear limitation of the scope, this article assumes that requirements management is a necessary part of the daily project management [12, 13] and that the customers of the case company only have one supplier of building elements and man-power, who is responsible during the entire life cycle of the building.
This article is build up in the following way:
3. Literature review, 4. Research and design methods, 5. Observations, 6. Description of case, 7. Discussion of results, 8. Conclusion.

3. LITERATURE REVIEW

For being able to implement requirements management in the case project, mainly literature in the areas of requirements management, construction, and project management has been studied. For the described case project and therefore for this article the author believes that Fernie [14], Girmscheid [15, 16] and Krönert [13] are very relevant authors, as they are among the few who have a clear theoretical contribution to requirements management in the construction industry. Additionally Girmscheid has an impressive amount of publications covering many other useful aspects (as e.g. life cycle considerations, decision making, and a systems view when it comes to requirements) related to the construction industry as well.

For the generic project management part of this article PMI's PMBOK guide [12] and Kerzner [17] have been chosen, as they appear to cover the very most aspects of project management. This seems to be supported by the large amount of global practitioners using those two books. As for the project management part that is specific for building projects, mainly Girmscheid – but also Krönert – are able to deliver again.

The INCOSE systems engineering handbook [18] has been selected because it covers many of the areas of this article from a technical, system, and life cycle point of view.
Chapter three expressed in table form looks like this:

	Fernie [14]	Girmscheid [15], [16]	Krönert [13]	PMBOK [12]	Kerzner [17]	INCOSE Systems engineering handbook [18]	This article
Requirements management in the construction industry – theoretical contribution	X	X	X	Supporting	Supporting	Supporting	X
Requirements management in the construction industry – practical application	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	X
Requirements structure covering the life cycle of a building		X (high level proposal only)	X (high level proposal only)				X
Project management		X	X	X	X	Supporting (strongly)	Supporting
Running several projects in parallel				Supporting	Supporting	Supporting	X
Practical implication of several life cycles of a different nature applying at the same time	Supporting	Supporting		Supporting	Supporting	Supporting	X
Technical systems / Systems engineering	X	X	X	Supporting	Supporting	X	X

Table 1: Main literature covering the key areas of this article. "x" means coverage of a certain area by a certain author

The combined literature list from above shows that several aspects still need coverage: the practical application of requirements management in building projects and a requirements structure covering the whole life cycle of a building and thereby future events. Furthermore, there seems to be no literature covering the situation of running building projects and developing product platforms, products, and new technology that is needed in those building projects in parallel. The aspect of several life cycles of a different nature applying to a project in the construction industry at the same time presumably is nowhere found in academic literature. As a consequence, the research described in this article is positioned as shown in Table 1.

4. RESEARCH AND DESIGN METHODS

The research described in this article is a combination of action research [8, 9] and a case study [7] where there was full access to all key people and complete insight into all documents relevant to this research; including documents containing the future strategy of the case company and its products. At the time of writing this article the research project just entered the second out of four action research cycles. The pre-step explained in "Action research for operations management" [8] has not been counted as a cycle here.

An interview round with all key persons has been conducted, covering all parts of the value chain of the case project (see Figure 3) including the projects described in the chapter "Description of case". In fact, most data of this case study have been gathered during this interview round, meetings with the project stakeholders, and clarification meetings with the project teams. Please note that in the case company the customer is not the end user. Residents are end users.

The interviews have been conducted using the same questions for all participants and resulted in a master document that covered a wide range of different requirements: from functional, non-functional, technical, market, organizational requirements, to requirements towards the project manager and requirements to the stakeholders themselves.

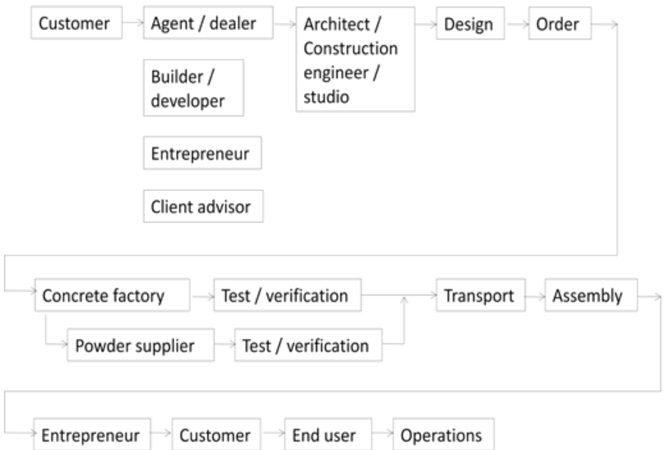


Figure 3: The value chain of the case project Footnote 1: More scenarios do exist

The authors' main task on the case project was to implement requirements management and to develop a suitable requirements structure containing all requirements of the different projects in one place, analyzing them, and linking the results to the case project's time schedule and risk register. This framing of the project work was advantageous, since the three knowledge areas – project scope management, project time management, and project risk management – are interconnected [12]. This active participation in the project has created project results that have been checked by the project staff and approved by the project manager and the project steering group. Especially the authors' proposals for how to group and prioritize the different requirements as well as the overall requirements structure, covering the different projects that are being run in parallel, has most certainly influenced the course of the case project. This can be seen by the fact that the recommended prioritization of some of the requirements over other requirements [19] and the proposed requirements structure has been widely followed by the project group. This approach is fully aligned with the principle of action research.

"The data analysis started during the interview round and continued thereafter. The research problem, questions and theoretical lens were applied as central pillars guiding the analysis of the case data. This involved an iterative and progressive process of questioning, reflection, theorizing and verifying each data.

The main task of the data analysis was first to gather [20]" all requirements of the different projects in the case company. Then all collected requirements were studied and structured considering the life cycles of:

a) the buildings made from the HPC of the case company,
b) the requirements themselves,
c) the building projects, and
d) the technology development project.

The reason for looking at those life cycles was that they were used for taking decisions on how to prioritize the different projects over each other and implicit in that the resources allocated to those projects. A deeper explanation of the life cycles will be given in chapter five.

The expected result of the data analysis was to get a deeper understanding of how requirements management can be applied to the construction industry and how a requirements structure that can cover the whole life cycle of a building including the technology development-, product development-, and product platform development could look like.

To accomplish this, all project goals [15, 16] were clearly stated and an overview table showing all expressed requirements was made. After that the project manager and the author agreed upon the relevant phases the different requirements had to be mapped into. The filled in overview table was then analyzed with respect to finding a suitable requirements structure that also considers future events.

The author is aware that Kamara et al. state "the requirements management process can be supported by using general software tools like DOORS [21] and RequisitePro [22] as no widespread requirements management tools are available in the construction industry" [23]. For reasons of transparency and flexibility in the data analysis no requirements management tools have been used in the case project.

5. OBSERVATIONS

While working on the case project a series of observations has been made. As discussing them is important for the success of the case project they will be covered by this article:

The phenomena that requirements management has not had its breakthrough in the construction industry, yet [15, 14], is quite interesting. In this case project, it has been examined if it is generally not possible to successfully apply requirements management to the construction industry or if this sector is simply lacking behind.

The phenomena of finding an appropriate requirements structure that tries to take future events into account and the subsequent application of requirements management to entire life cycles will also be looked into:

As fossil fuels are getting scarcer and the global warming continues to increase houses, that are being built today, will be met with a constantly increasing number of requirements on building stock from the EU. Especially requirements that are related to CO_2 emission and to the materials that are used for building and remodeling will be in focus. Additionally, sensible safety requirements like, e.g. "K1, 10: a wall is only allowed to start reacting to fire after having been exposed to flames for at least 10 minutes" [24], are also constantly getting revised as new materials are put on the market.

Birgit Rasmussen [25] estimates that more than 50 out of approximately 500 million Europeans suffer from noise because their residences are not sufficiently sound insulated. It is the author's belief that the EU will also introduce new, common requirements for sound insulation in the not so far future.

On top of that are the country specific and local requirements such as the traceability of materials used in a building, as well as the self imposed requirements, e.g. when a building owner decides to remodel her building.

Since the above listed events are strongly expected or are already known to happen in the coming 50 to 100 years, it is beneficial for the case company to design a requirements structure that takes all known or assumed requirements of a buildings' life cycle into account. In fact the intention to do this has explicitly been specified in the company's philosophy.
By doing so the company can position itself as the sole supplier during the whole life cycle of a building, as already today it can make customers being aware of future requirements, the estimated price tags attached to them, and the fact that they are ready to be at the customers' side for as long as the building exists. Supported by requirements management, the corporation can in the same entire period document the content of its products. Besides, the case company will be more prepared for the future by trying to anticipate upcoming events.
The author is aware of the fact that requirements management is considered to be a supporting management process that ends at the end of the building project [13]. But, as argued above, the scope of this article is beyond a single building project, as it tries to cover the whole life cycle of a building.
The phenomena of running technology development, product platform development, product development, and a portfolio of building projects in parallel seems not to be covered by academic literature, as it is a rather special case. Nevertheless, this is reality in the case project.
Before looking at a more detailed description of the case project, the observation of several life cycles of different natures applying to the case project at the same time has to be mentioned here:

1) The life cycle of a building in the case project:

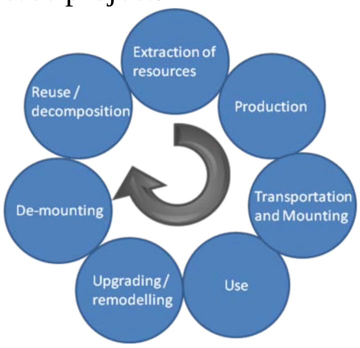


Figure 4: The life cycle of a building as met in the case project

Other product life cycle stages and a concept for life cycle design can be found in [26].

2) The life cycle of a single requirement in the case project is shown in Figure 5:

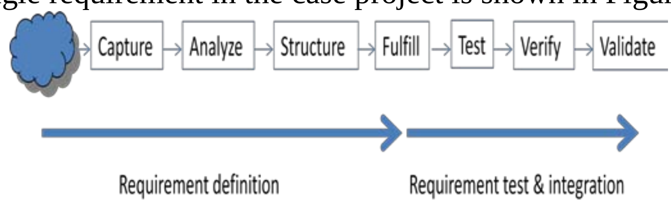


Figure 5: The generic life cycle of a requirement as encountered in the case project

The life cycle of a requirement can be divided into two main phases: The requirements definition phase and the requirements test and integration phase. The requirements definition phase consists of the following steps:
The *cloud* represents a high level trigger event, e.g. the start of a project. *Capture* means that the requirements manager is asking the different stakeholders for their requirements – the single requirement, whose life cycle we are interested in – is being stated. This requirement is then *analyzed* and – if not rejected during the analysis – put into a requirements *structure*. As the project progresses the requirement is *fulfilled* and ceases as such to exist.

Now the requirements test and integration phase starts: the person who has fulfilled the requirement needs to *test* that this really is the case. After that the person who is responsible for the work package [12], of which the fulfilled requirement is only a portion of, evaluates that this requirement and all other requirements of that work package have been incorporated *in the right way (verify)*. The final step is to *validate* the requirement meaning that it has to be ensured that the requirement actually *meets the user's needs* and that the *specifications were correct to begin with*. This is typically done on a system level. During all those phases the single requirement gets more and more integrated into the total pool of requirements.

A practical example from the case project: The building project for building 75 row houses in Aarhus gets started (cloud). Specifications have been agreed upon between the case company and the customer. In order to live up to specifications the project stakeholders were asked for their requirements. One of the many requirements that had been captured was that the row houses have to be self supporting when it comes to heating. An analysis of this requirement confirmed that it is a sound requirement that the case company can live up to and wants to fulfill. Therefore this requirement has been accepted and put into the requirements structure of the building project. Once this requirement is met it stops to exist. The craftsman assembling the required heating solution to the row houses needs to check his own work and that this requirement has been fulfilled. Later in the project the owner of the work package "pipes and heating system" evaluates that the requirement has been incorporated in the right way. During the validation the requirements manager makes sure that the requirement still meets the user's needs and that the agreed specifications are correct. Once this has been done the life cycle of this single requirement has been concluded.

3) The Connovate project basically uses the life cycle phases as shown in Figure 6. A more complex example of the life cycle and phases of a building project can be found in [27].

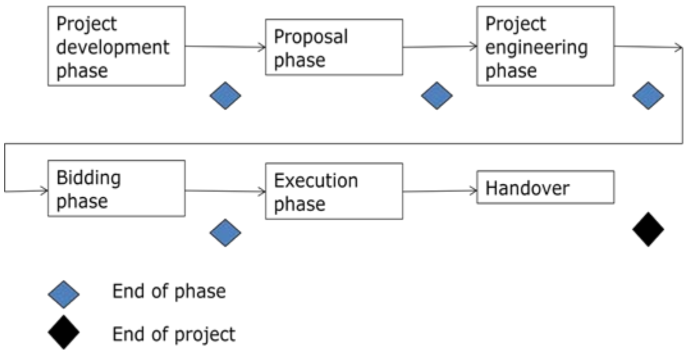


Figure 6: The phase model used in the case project

4) The new technology that is developed in this project are extremely thin but highly insulating HPC sandwich elements, additives to the powder that is used for producing the HPC, and many different ways of mounting and surface treatment of the HPC sandwich elements. Due to patent considerations the new technologies will not be described in detail. It is assumed that the life cycle of technology consists of the traditional four phases:

- Research and development phase
- Ascent phase
- Maturity phase and
- Decay phase

Even though the nature of the above life cycles is different and the requirements linked to them vary a lot, from a time perspective it makes sense to map all four life cycles into one overview picture which helps taking decisions on what to do when and how to distribute scarce resources as it in the case project neither is possible nor seems right to work on all requirements at the same time. The vertical, gray line in Figure 7 shows a commonality three of the four life cycles have: the time stamp T1. When the building project is over, the requirements have been validated and the use of the building starts. T1 also serves as a checkpoint where the upper three life cycles and thereby their requirements should, for reasons of steering the case project, approximately be in synch. Please note that this is only a schematic comparison. The different life cycle phases can have other lengths than depicted here.

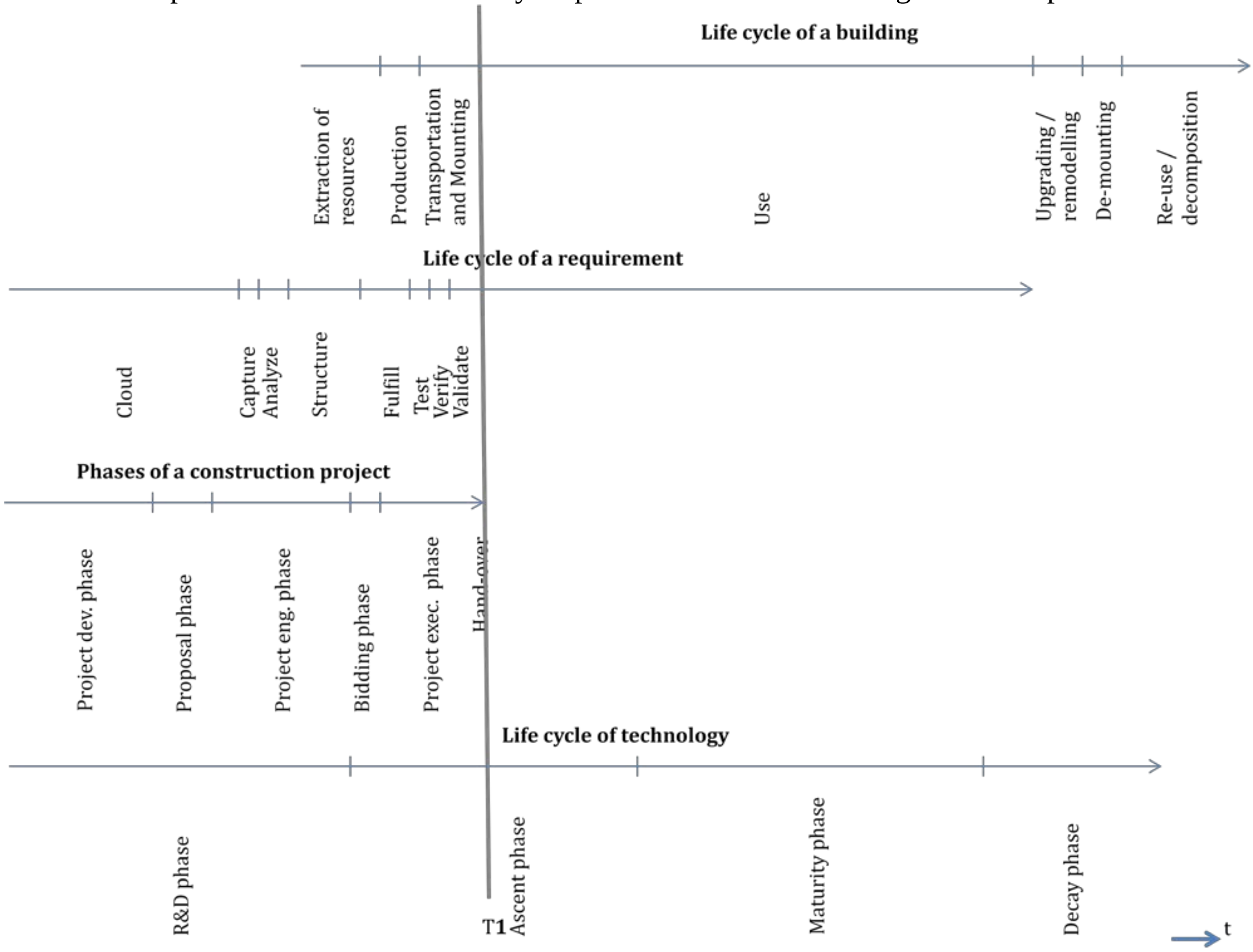


Figure 7: A schematic comparison of the different life cycles from a time point of view

One could argue that, while running a building project, in reality one typically already works in several project phases at the same time (even though there is a phase model with milestones one should comply to) and on top of that, work is done in up to four different life cycles simultaneously. Having to take decisions in such an environment where main parameters like technology, product platforms, and market can change, too, imposes many high risks on the case project. In order to reduce those risks and to keep track of so many phases all at once, the application of requirements management is once more justified.

6. DESCRIPTION OF CASE

Background of this research

Even though the case company is profit oriented like most other companies it has acknowledged the necessity to do research in some areas in order to move the Danish construction industry and society forward. For this reason, six PhD projects have been initiated where this article describes the findings of one of them.

Purpose of the case project

The described case project has the purpose to produce low energy buildings and insulation panels of pre-fabricated High Performance Concrete (HPC) sandwich elements based on new technology. At the same time the case project wants to live up to EU's 2020 energy consumption requirements.

Structure and goals

The case project consists of the following sub-projects:

- A technology development project with the goals to develop extremely thin but highly insulating HPC sandwich elements, additives to the powder that is used for producing the HPC, and many different ways of mounting and surface treatment of the HPC sandwich elements
- A product development project with the goal to develop new sandwich elements and jointing in different dimensions
- One (and soon two) platform development project(s) developing a low cost / high end platform
- Two (and soon a portfolio of) building projects:
    1) In the city of Aarhus, Denmark, 75 row-houses – consisting of two floors – are currently being erected using the case companies HPC sandwich elements based on a newly developed technology. This is part of the high end building product platform.
    2) In an African country a house, consisting of one floor and 40 m^2, has been built as a show case also using the case companies HPC sandwich elements based on the same newly developed technology. This is part of the low cost building product platform.

The sub-projects have many dependencies between them. The strongest dependencies are sharing the same human and financial resources, where possible life cycle views were used to prioritize between the sub projects and to distribute resources between them. In some cases constraints, like the new technology, have to be developed first, before they can be used in the other sub projects implicitly decided where to use the resources of the case project.

As mentioned in chapter five "Observations", people typically worked in several phases of especially the building projects at the same time as well as on several life cycles simultaneously. This gave a very dynamic and innovative environment, where requirements management could be used as one of several counter measures to maintain the necessary structure that is needed in a project.

To understand the complexity of this case project it is important to know that it gets its human resources from 6 companies and 5 research institutes. Three of those 6 companies comprise the core team and have the main responsibilities as they own the case company together. The remaining companies deliver expertise on authority requirements and knowledge of the markets in different countries. The research institutes participating have their expertise in construction (statics, insulation, and ventilation), product development and product configuration, as well as in management. All participating companies and institutes are placed in Denmark.

Using action research on such a dynamic case project seemed to be the natural choice and has so far proven to be beneficial.

7. DISCUSSION OF RESULTS

The research conducted in the case project gave a series of results that have been divided into the main areas this article aims at covering:

Introducing requirements management to the construction industry:

Some of the top companies working in the field of construction in Denmark have been visited and asked for their way of managing requirements and implementing them into their projects. They also got asked for the tools and processes they use when running a building project.

It was surprising to see that none of those companies had a complete overview of all the requirements that relate to the same building project gathered at *one* place – regardless the type of building project. Only one of those companies used a standard software tool for managing their requirements (but not the requirements of their sub contractors). Contacting one of their industry associations confirmed that picture.

Note that concerning the content of a building delivery it is customary to rely on norms and standards that cover quality, safety, indoor climate, and many other aspects [28 to 32]. Those aspects will be checked during the hand-over procedure between the entrepreneur and the customer. Instead, one could first explicitly list all known requirements in one place – even though they are often a repetition of applied norms and standards – and then define the gap. This could be done much earlier in the project which has been confirmed during company visits and the interview round.

Therefore, when starting in the case project, the application of requirements management had been discussed. Even though it was anticipated to be time consuming to implement and maintain requirements management in the case project, the benefits were expected to exceed the investment. The expected main benefit was to have a completely defined and accepted scope that accelerates the process of making a time schedule and gives plenty of input to the risk identification process. Furthermore, documenting the requirements enables sufficient testing of all relevant parts of the projects that the case project consists of. Apart from that, it seemed hard to develop new technology or pass authority approvals without an overview of all relevant requirements. For those reasons, the project manager and the project steering group of the case project agreed to implement requirements management in two steps. First, requirements management was implemented covering the technology development, the product development, and the building projects. Then, the scope was extended to also cover product platform development and the whole life cycle of the buildings that are to be delivered.

After that decision had been taken, the different key stakeholders of the case project have been visited for an interview round on their requirements. During the interview round, the interviewees were rather dedicated and contributed with a lot of information and many requirements that were not covered by norms and standards. They fully supported the decision to implement requirements management and did not find it hard to understand the processes related to it.

Already while conducting the interviews the usefulness of requirements management showed itself.

A question like: Should the building de designed to last 50 years as stated in [4] or should it be 70 or even 100 years got visible and could be thoroughly discussed as soon as the stakeholders found out that they assumed different life times.

The question of how many percent of a buildings' material should be reused showed itself when the different requirements, gathered during the interviews, were mapped into the Excel-file that covered all requirements stated for the case project. It clearly showed different expectations towards reusability. The Excel-file containing all known requirements supported the process of taking vital decisions on an informed basis as the gathered data could be grouped, filtered, and analyzed easily.

A third example of a result: while stating and comparing various requirements, the different stakeholders realized that they had had diverse expectations towards which market segments should be served presently and in the future. It needed to be clarified and communicated which market segment to serve first.

A fourth example showed that some phases of the building project had a poor coverage when it comes to requirements and test. After this had been recognized the missing requirements and tests have been identified and documented.
The last example is on the benefit for the project manager who now has *one* place containing all requirements of all projects he is responsible for, which makes filtering, e.g. the requirements for the different phases and the persons responsible for them, very easy. This enhances status reporting and writing project newsletters.
When all requirements had been mapped into the Excel-file the data was carefully reviewed, as the requirements had to be correct and unambiguous [33] and people got assigned to different groups of requirements. From there it only took a few weeks until a risk register and a time schedule had been available, which confirmed that the initial expectation of benefits was correct.
There were more practical examples of the results of applying requirements management to the case project. All of them pointed into the same direction: it is possible to successfully implement requirements management to at least parts of the construction industry.

Running several projects in parallel:
The case project consists of the following projects that are run in parallel: technology development, product platform development, product development, and two building projects. Applying requirements management, life cycle perspectives, and a division of phases to the case project, made it apparent how many projects are actually being dealt with. This was an important event in the case project, since discussions and decisions on e.g. where and how to spend resources could be based on the same picture of the world. There was also a transparency of the places where the same requirement was applicable to different projects. Especially the two in chapter six described building projects have some commonalities. Those commonalities can be used later on in the project since some test, verification, and validation results can be re-used.
The Excel-file containing the complete set of requirements for all projects, that are part of the case project, helped getting and maintaining total control of the project scope that is subject to constant revision. From an operational point of view it has so far been possible to use requirements management in a multi-project environment.
When working with requirements management in the case project one curiosity has been discovered. Typically one would expect to first have some requirements in place and then to find a practical solution to them. In all the mentioned projects once in a while it was the other way around: a possible solution was found and then the requirements were derived from that. This could be one of the main reasons for not applying systems engineering 1:1 as taught by the book.

Covering the whole life cycle of a building and considering future events:
After having conducted a series of 11 interviews, as well as stakeholder and clarification meetings, all gathered requirements had been analyzed with respect to the company strategy. The result was a list of possible future events that are likely to occur and that are probable to have an impact on: primarily the requirements on the building during its life cycle but also on the development of the company itself, the product portfolio offered by the company, and the technology developed by the company.
An adequate requirements structure for the case project should be divided into logical areas, cover parallel projects and different types of requirements, and should try to consider relevant future events as well as the life cycle of a building. In the case project the requirements structure has been divided into the areas “company level”, “technology level”, “product platform level”, and “building / physical object level”, as this division was considered the most suitable to control the single projects and at the same time to communicate with the project steering group and with other stakeholders. Other generic requirements classifications are possible. An example can be found in [34].

Identified possible future events leading to new requirements on:

company level

- The company's financial capabilities are changing which can impact the price of future deliveries and support
- New markets are being entered. E.g. investment and operational expenses requirements differ between countries
- New customer types are being served resulting in new scenarios
- Customer requirements are changing over time as a tendency
- Requirements are introduced due to branding. E.g. buildings are used as show cases
- Production requirements are changing and thereby impacting future deliveries. E.g. different format, price, quality
- New requirements associated to the cradle to cradle principle, not covered above, are being introduced

technology level

- New technology requirements are coming up. E.g. walls that are thinner than the current two centimeters limit or elements that last longer than they currently do are being requested. This is relevant for future sandwich elements
- New abilities of the material like e.g. a surface protection layer are desired
- New kinds of joints are needed
- 100% reusability of the materials that are used in the building is demanded by law
- Decomposition of materials that cannot be reused – if any – is possible

product platform level

- Different new product platforms might emerge in the future. Reusing parts of the existing platforms has to be possible
- A product platform ceases to exist and will be replaced by another platform. This is only allowed to have a positive effect on existing buildings
- Several new kinds of buildings (product families) have to be supported by existing platforms
- Existing product platforms will change over time. A modular build-up is required. Clear interfaces need to be defined and documented
- A product configurator will be made per platform

building level / physical object level

- New element sizes and types are needed (this can also result in new technology requirements)
- Stronger energy insulation requirements are forced upon the buildings by e.g. the EU
- Stronger sound insulation requirements are forced upon the buildings by e.g. the EU
- Stronger safety requirements are forced upon the buildings by e.g. local authorities
- Indoor climate requirements are enforced by law
- New regulatory requirements are being introduced
- New requirements are imposed by the municipalities
- Requirements for buildings being self supporting regarding heat and electricity are forced upon the buildings
- Replacement of sandwich elements is necessary and has to be possible
- Upgrading of buildings. E.g. further wiring, additional sinks is needed
- Remodeling of buildings. E.g. adding a room is needed
- Mounting and demounting of entire buildings has to be efficient
- Traceability requirements for the materials used are getting stronger
- Transportation has to consume less CO_2

The above possible future scenarios are in no way exhaustive but are the current result of the project team's work.
The successful coverage of the above listed possible future events is anticipated to positively contribute to positioning the case company in the market during the entire life cycle of a building. Furthermore the company is better prepared for the future and estimates of a building's entire life cycle cost can be made as it often is requested by possible investors and by some other customers. This has been confirmed during the interviews.
Looking at a whole series of possible future events and the requirements derived from that – while still implementing the requirements from the present – leads to many trade-offs. Here are some practical examples from the case project:
Trade-offs in a multi-project environment are often encountered when contradictory requirements from the different projects have to be prioritized over each other, for instance when a building project needs a new jointing system for attaching the HPC panels to the walls of a building within a few months but the technology project wants to spend more time on testing the new jointing system with the HPC elements before releasing it to the market.
Being prepared for the future costs money and is in our case often a speculative process. Despite the investment an area like the production of the sandwich elements has already been prepared for future events by buying the right, adjustable equipment and implementing flexible processes.

Having solutions in place that make future de-mounting of the building fast and easy also saves time and money in the long run, but costs money to design and implement in the present.

Another example of a trade-off is the low thickness of the concrete panels. It is today as low as two centimeters and it has taken a considerable amount of time, technology development, and approval testing to get there. Reducing this thickness even further will give additional advantages in the market but will at the same time be very resource demanding.
Analyzing trade-off scenarios often results in a go or no go decision. Generally before jumping into investments one should evaluate the probability of future events and the expected profit from the intended investment.
A very simplified extract of the requirements structure that is used in the case project today is shown in Figure 8 in Annex A. To demonstrate how future events are considered in the structure an example of changing from EU's 2020 to EU's 2025, energy consumption requirements have been added to it. The example visibly shows the interconnection of future events and thereby requirements.
Analyzing the new requirements structure filled in with all found requirements gave the following results:
Out of over 800 new requirements more than 500 requirements have been identified that were not covered by norms and standards

- In order to cover possible future events and to have a suitable requirements structure no new headlines for requirements groups had to be added to the main level (root level; see Figure 8 in Annex A) of the Excel-file covering all requirements. It was sufficient to only add "future event requirements" to the sub-levels. Re-grouping only a few requirements was enough to get the division "company level, technology level, product platform level, and building level".
- After the re-grouping the requirements structure has at the time of writing this article been stable for about five months
- The biggest amount of decisions that had been taken in the project was when requirements were prioritized and / or divided into work packages
- Situations where two solutions – without a previous conscious decision having been taken – were run in parallel; e.g. a product platform for high end customers and a product platform for low cost housing were targeted at the same time; it became visible that they had to be prioritized over each

other. At least a decision had to be taken if work on more than one product platform could be maintained at the same time or if one product platform had to be postponed

- The added future requirements were typically interconnected, meaning adding new requirements in one area normally resulted in the need to add new requirements to several other areas (see example in Figure 8 in Annex A)
- It got confirmed that the entire life cycle of a building and possible future events so far can be covered by the requirements structure made in the case project
- Applying the new requirements structure also had its trade-offs:
    - The time consumption, for finding possible future events which then in detail are mapped into the existing requirements structure, can be rather high. Here it is necessary to find the point where the extra hours do not yield the correlating extra benefit
    - It is hard to tell what the most likely and the least likely possible future scenario is. There is a risk that the resources are spent on the wrong scenario
    - Having a complex overview sheet showing all requirements and then adding future event requirements to it can make it difficult to keep the total overview and focus. Working with requirements management tools is preferable. Especially when handling requirements updates

Encouraging practical results have been delivered in all areas this article wants to cover. Requirements management has successfully been implemented in the case project and a suitable requirements structure has been found. Both have so far been tried out successfully in a multi-project environment. It is now time to use requirements management on other buildings and building projects of the case company before applying the new knowledge to other areas of the construction industry.

8. CONCLUSION

By applying requirements management to the described case project it has been shown that requirements management successfully can be applied to at least some parts of the construction industry. This has been done in two steps: first, requirements management was implemented covering the technology development, product development, and the two building projects. Then, the scope was extended to also cover product platform development and the whole life cycle of the buildings that are to be delivered. The reason for doing so was that – as explained in the article – a lot of new requirements will be forced upon a new building during its lifetime.

Focusing on the entire life cycle has its advantages as one is forced to think about future events and their likelihood to occur. It also supports estimating the life cycle cost of a building and the cost of possible future events, which is relevant to know for possible investors and buyers.

In order to come that far, it was essential to find a smart requirements structure that tries to consider future events and that can be used in a multi-project environment. In this article a simple and practical attempt for making such a new requirements structure has been demonstrated.

During the next two years the usefulness of the proposed new requirements structure will be observed in the case project. In that period it is also intended to apply the found requirements structure to other buildings and building projects of the case company in order to verify and improve the structure even further. The predicted future requirements will be documented and analyzed as they become a reality.

The use of requirements management in the construction industry looks very promising but is still at an early stage. Therefore more practical experience and further research is needed.

Future research

After having looked into getting an operational requirements structure it will be interesting to do future research in the following vicinities:

- The use of requirements databases and processes especially designed for the construction industry

- Training of key personnel in requirements management. A whole field needs to be educated in the practical application of requirements management. How can training of a whole field be done in an efficient way?
- How does introducing requirements management to the construction industry impact this industry and its customers in the long run?
- Is the project management model used in the case project the best choice when working with the new requirements structure and the different life cycles?
- The probability of the occurrence of the found possible future events has to be looked into so that a life cycle cost model and tool can be made that has a practical use for possible investors
- Data on the stability of the requirements have to be collected. This will also contribute to the making of an operational life cycle cost model and tool

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ANNEX A: Figure 8: Extract of a simplified requirements structure that considers future events

Main level of the Connovate requirements specification: Requirements types vs. Levels	Sublevel 1 (category)	Sublevel 2	Sublevel 3
Requirements on company level			
Country specific requirements	Country A Country B		
Market related requirements	Types of buildings	3 rooms on one floor 60 m2 building 5 rooms on one floor 140 m2 building	
Requirements caused by different customer types	Housing association		
	Governmental program		
Customer requirements			
Financial requirements	Cost for establishing		
	Running cost		
	Other cost	If less elements can be transported due to increasing thickness the Business case has to be updated	
Branding requirements			
Production requirements		Find out whether the new elements cause any problems in production	
	Under what conditions do we produce?		
	Modularisation requirements		
Project management requirements	Requirements to the project manager		
	Cost requirements		
	Communication requirements	Dependencies to other stakeholders	Requirements for addressing the market to tell that we can deliver new elements that live up to EU's 2025 energy saving requirements
		Requirements from your unit	
	Personal requirements		
	Innovation requirements		
	Research requirements		
	Requirements due to risk management	Find the risks related to changing to new elements	
	IPR requirements		
	Organisational requirements		
	Quality related requirements		
Requirements on technology level			
Technological requirements	Requirements to the additives		
	Requirements related to the processes related to technology		
	Requirements related to decomposition		
	Requirements related to traceability		
General technical requirements	Requirements related to processes		
	Requirements related to the whole system		
	Requirements related to development		
	Requirements related to test and verification		
	How are the acceptance criterias defined?		
	Requirements related to insulation	**It is enforced that all existing houses have to live up to EU's 2025 energy insulation requirements**	
	Requirements related to mounting		
	Requirements related to concrete		

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	Requirements related to additives		
	Requirements related to installations	Find out where the installations are placed in the new elements	Update technical drawings and programs
	Requirements related to fibers		
	Requirements related to the surface		
	Requirements related to transportation	Check whether the new elements are thicker	If they are thicker less elements can be transported at the same time How many elements can be transported on one truck
	Site requirements		
Requirements on product platform level	Low cost housing product platform	One floor	40 m2
		Two floors	40 m2
	High end building product platform	One floor	140 m2
		Two floors	140 m2
Requirements on building level / the physical object level			
Requirements related to the building and its elements	Physical requirements to the sandwich elements	Check the physical parameters of the new elements	Make action plan if necessary
	Physical requirements to the joints		
	Requirements to tolerances		
	Precision of measurements		
	Bearing elements		
		Joints	
	Facade elements		
		Joints	
	Transformation facade		
	Supporting divider		
	Non-supporting divider		
	Roof		
	Deck		
Regulatory requirements	Authority requirements in specific areas		
	General authority requirements	EU's 2025 energy insulation requirements	
	ETA / CE		
	Applicable local norms		
	Environmental factors		
	Safety	Check whether the new elements still live up to safety requirements	
	Life time expectation	Predict the lifetime of the new insulation material	Run aging tests
	Fire / fire classification	The new elements need to be fire approved	Book a K1 10 test
	Sound	Having a different insulation requires further sound tests	Sound test 1 Sound test 2 Sound test 3
	Indoor climate	The indoor climate needs to be checked again	Make test plan Book test Execute and analyse results
	Requirements to the underground		

ARTICLE 2 REQUIREMENTS MANAGEMENT FRAMEWORK

A Requirements Management Framework for Construction Companies Offering Pre-defined Products

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A Requirements Management Framework for Construction Companies Offering Pre-defined Products

Michael Wörösch

(Corresponding author, mailto:mwch@mek.dtu.dk, +45 27 11 41 42)

Hans Peter Lomholt Bruun

Thomas J. Howard

Niels Henrik Mortensen

Department of Mechanical Engineering

Section of Engineering Design and Product Development

Technical University of Denmark

Produktionstorvet

Building 426

2800 Kongens Lyngby

A Requirements Management Framework for Construction Companies Offering Pre-defined Products

1. ABSTRACT

The construction industry faces many and frequent project management related issues, such as: cost overruns, project delays, poor profit margins and disgruntled stakeholders. This is at least partly due to ineffective requirements management. Through a literature study, action research, and 30 interviews undertaken with 12 construction companies and one authority, this article shows the ad-hoc nature of requirements management practice in the Danish construction industry. Core considerations are identified that are ignored in formal practice, such as, life-cycle related requirements, requirements testing / verification / validation and project results analysis. The study also shows that key literature in this area is weak at representing these considerations, as well as network related requirements and appreciating the differences in project types. Based on this study, a framework for formal requirements management is proposed, consisting of 14 core requirements management building blocks. This framework can be used as a tool that allows managers of building projects to manage *all* the requirements they encounter on their projects. Furthermore the framework helps overcoming the shortcomings that were identified using action research and during interviews. For validation purposes the framework is applied to two new construction projects of a case company, gaining positive feedback with a strong desire to roll-out the framework for future construction projects. On viewing the framework, several of the other interviewed companies stated their interest in applying the framework, too.

Key words: Requirements management, conceptual framework model, construction

2. INTRODUCTION

Many studies have indicated that one of the major challenges in project / construction management is in the formulation and management of project requirements (Yang et al. 2012). Even though there has been an increased focus on the formulation and management of requirements on construction projects (Yang et al. 2012), no supporting frameworks for managing requirements from end-to-end in the construction industry have been identified by the authors during an extensive literature review.

According to Oberg et al. (2000), requirements management is defined as: a) a systematic approach to eliciting, organising, and documenting the requirements of the system, and b) a process that establishes and maintains agreement between the customer and the project team on the changing requirements of the system.

The construction industry in Denmark can be characterised as having a business environment where:

- Labour productivity is low in comparison to other industries (Kristensen 2011).
- Profit margins are as little as 1-3% (Jespersen 2012).
- There are frequent bad headlines reporting delays and project overruns.
- There is often substantial rework and poor quality in construction projects, and
- Companies are closing down on a weekly basis (e.g. in Denmark the number of construction companies has gone down from about 36.000 in 2008 to estimated 29.500 by the end of 2012 (Denmarks Radio 2012; Statistics Denmark 2013)).

The authors believe that this undesirable situation can be partly put down to the lack of interest and uptake of project scope management (PMI 2013) and in particular, project requirements management (PMI 2013, p. 105 ff) which both are described in the PMBOK (PMI 2013). Or as Fernie et al. (2003) express it: "The dominant storyline in the literature *exhorts* the adoption of requirements management with reference to a number of longstanding problems that are all too familiar to the construction industry:

- failure to deliver projects within budget;
- late delivery of projects;
- failure to consider project decisions from a "whole life cycle perspective"; and
- poor customer satisfaction."

Yu and Shen (2013) agree with the fact that the use of formal requirements management in the construction industry is currently very limited and advocate introducing a systematic procedure to tackle the management of client's needs and requirements.

This paper first reviews the literature related to requirements management and requirements management in construction in particular and then assesses the state of the art throughout the Danish construction industry offering pre-defined products. Alfen et al. (2014) have special focus on builders' merchants and what those have to be able to provide to construction companies. For that purpose they divide the construction industry into two poles – POL-1 and POL-2. POL-1 describes the part of the construction industry that builds according to the requirements of the owner (service provider, mainly using the design-bid-build type of contract). POL-2 describes the part of the construction industry that offers pre-defined products (e.g. a type of house or pre-fabricated elements). Most construction companies are within POL-1. The data of this study are mainly from POL-2.

Based on the summary of these reviews constructed from 30 interviews over five interview rounds and experiences from a case project, a comprehensive approach to requirements management a – Requirements Management Framework (RMF) – is proposed. This framework can be used as a tool that allows managers of building projects to manage *all* the requirements they encounter on their projects. Furthermore the framework helps overcoming the shortcomings that were identified using action research and during interviews as it takes important elements such as:

- A life-cycle perspective.
- Addressing the gap of not having an end-to-end process for handling requirements in construction in a pragmatic way.
- Ensuring that major activities as stating goals at project start and comparing achieved results to the stated goals at the end of the same project.
- Managing, testing, verifying, and validating requirements.
- Seeking knowledge from other companies within the network.

from best practice, chosen due to their successful application in other projects and industries. The carried out interviews revealed that this is often only done partly and sometimes not at all as shown in Table 1 in section 5. The proposed approach is then discussed in detail with reference to observations and validation made when applying it to two new construction projects. The article ends with a conclusion and proposal for future work.

3. RESEARCH METHODOLOGY

The research methodology that was applied to this study can be divided into three parts.
(1) A literature study was done focusing on requirements management in general and requirements management in the construction industry in particular. The literature study is described in section 4.
(2) Action research as described by Coughlan and Coghlan (2002) was done at a case company. For that the research project was divided into a pre-step and four action research cycles.
(3) 30 interviews (semi-structured and structured) were conducted at the case company, several other construction companies, and industry specialists. Those interviews revealed that managing requirements on a construction project is considered to be challenging. This can be put down to the sheer number of requirements that have to be managed and stakeholders who have to be considered. As special rules apply to research interviews, guidelines provided by Kvale (1994) and Girmscheid (2007) were applied. Please note that some of the largest construction companies in Denmark are among the interviewed companies.

Based on data acquired from the above the Requirements management framework for the part of the Danish construction industry that offers pre-defined products was developed and then validated on the case project and a test house building project.

4. LITERATURE REVIEW AND STATE OF THE ART

In order to create an affective requirement management approach for the construction industry, the literature was consulted, mainly focusing on areas such as requirements management, requirements management in construction, systems engineering, construction, and framework models. Literature was reviewed cautiously in-light of comments by Fernie et al. (2003) who state that requirements management approaches may not map from one domain to another as the industrial context is too important. It was therefore vital to select only the components that were meaningful to the construction industry. Organisations such as INCOSE (2013), PMI (2013a), and IEEE (2013) have been key contributors in this context. This section briefly describes some of the main contributors to this research area, and summarises the status of the field.

The INCOSE systems engineering handbook (2011a) has been the main source of literature as it describes the concept of systems engineering and its system life-cycle processes and is seen to be aligned with project management processes and best practices as defined by the project management institute (2013a and 2013b). As systems engineering is an interdisciplinary field of engineering focusing on how complex engineering projects should be designed and managed over their life-cycles the general INCOSE handbook doesn't focus on technical domain knowledge. Therefore it is possible to apply systems engineering, or life-cycle processes, to many different industries. For the construction industry, it was though appropriate to adopt the following system life-cycle processes from the handbook: the stakeholder requirements definition process, the verification process, and the validation process, which were lacking in most construction cases. The guide for the application of systems engineering in construction (INCOSE 2012) was also consulted, as it is currently INCOSE's only guiding specification that is directed at the construction industry. In the in section 5 proposed framework the INCOSE systems engineering handbook (2011a) had been used to create the building blocks "Life cycle approach" and "Test, verification, and validation".

At present there exists plenty of literature on systems engineering (Aslaksen 2005; NASA 2007; DeHoff et al. 2012). Especially systems development and software development in the aerospace and defence domain are covered very well. But there is very little methodological contribution on how to practically apply systems engineering to the construction industry.

This situation is likely to change, as the INCOSE infrastructure working group in August 2011, declared in their charter (INCOSE 2011b) that it is their *long term plan* to bring construction companies into INCOSE (2013). Collaboration with the American Society of Civil Engineers (ASCE 2013) is one of the INCOSE infrastructure working group's stated midterm goals. These efforts in getting systems engineering expertise into the field of construction have also been developed, in parallel, by universities (Imperial College London 2010).

Aslaksen (2006) affirms that systems engineering equally applies to all industry sectors and its use being limited to the aerospace and defence industry has been for historic reasons. In a keynote speech at SETE (2006), Aslaksen made strong provocations for the suitability of system life-cycle processes for the construction industry. The authors share this view and believe them to be a necessary inclusion in requirement management of construction projects.

Professor Girmscheid, one of the leading experts in the field of construction and infrastructure management, has published research looking into the use of a life-cycle approach (Girmscheid 2008) and a model for requirements management, where requirements are linked to project goals, in the field of construction (Girmscheid 2010a and 2010b). This was another approach adopted to make the sheer number of requirements in the construction industry more manageable and meaningful and to ensure that construction projects deliver to goals. Girmscheids research was the base for the “Goals (START)” and “Results (END)” building blocks.

The Project Management Body of Knowledge (PMI 2013) gives a hands-on description of how project scope management should be done and shows the process steps that are necessary to undergo in order to have a clearly defined project scope. As having a clearly described scope is desired in construction projects, too the PMBOK has been applied. It is worth noting that in the PMBOK requirements management is part of project scope management. The building blocks “Organisation”, “Prioritisation and documentation of requirements”, and “Project execution and monitoring and controlling of requirements” are based on the Project Management Body of Knowledge (PMI 2013).

The IEEE Guide for Developing System Requirements Specifications, IEEE Std 1233-1996 (IEEE 1996) has been consulted as it provides some guidelines for what a requirements management process should be used to ensure. IEEE has a long history in requirements management and processes in general. IEEE has historically been very strong in specifications for software development.

As for project and requirements management specific for construction: In their book “Modern Construction Management” Harris and McCaffer (2012) cover many, but not all, core aspects of project management. Their focus lies in the areas of project management that are especially relevant in construction.

Barrie and Paulson (1978) offer an alternative to Harris and McCaffer (2012) in “Professional Construction Management”. They also focus on project management in construction. What makes their book relevant for this research is their section on “requirements of the professional construction manager” (pp. 44).

Kamara et al. (2000), Jeary et al. (2010), and Vijayamma and David (2010) have been studied as those articles describe how requirements management frameworks can be built up. Kamara et al. (2000) seem to offer the only requirements management framework within construction. Jeary et al. (2010), and Vijayamma and David (2010) have been identified as pedagogic examples outside the construction industry that have been used for formulating the requirements management framework at hand.

The above mentioned sources describe what requirements management and systems engineering are and how they are related to construction. They also give an impression of how requirement frameworks in some other industries look like. But no literature has been found describing the application of requirements management in construction.

5. THE REQUIREMENTS MANAGEMENT FRAMEWORK

This section provides a description of the shortcomings that have been identified in the way Danish construction companies manage their requirements on building projects (mainly POL-2) and, as a consequence hereof, the proposed requirements management framework as shown in Figure 1.

5.1 Identified shortcomings

Table 1 provides an overview of the components of requirements management and their presence in both literature and the construction industry. The literature and approaches addressing the gaps observed in requirements management practice (see Table 1) will be discussed for the remainder of this section.

The table is based on literature review and answers received during interviews at a case company, 11 additional construction companies spanning from 7 to 5000 employees and one authority. The size of the projects that those companies are running spans from single family houses of up to two floors over large housings to 200.000 m2 office buildings. All interviewed companies are active in all phases of their construction projects. What can be seen in Table 1 is that only 1 of the interviewed companies is applying a life-cycle approach and none of the companies is testing, verifying, and / or validating requirements regardless the size and uniqueness of their projects. In fact all interviewed companies are only performing the tests that are required by law. In the same interviews, the companies admitted to having regular delays of their projects; often due to rework.

What can be seen from the literature in Table 1 is that none of the frameworks covers the process steps that have been identified as being vital for successfully managing requirements on construction projects. E.g. taking into account the different types of projects a construction company is running in parallel or the network a project exists within is completely ignored. Table 1 also shows that only one of the identified requirements management frameworks did mention test. When interviewing experts from construction companies, ranging from large multinational to small single project firms, it became clear that construction companies running complex projects will receive more benefits when using the framework than those with low complexity. This is fully aligned with the application of systems engineering in general (INCOSE 2011a).

		Building blocks of the requirements management framework													
		Input	Goals	Processes	Life-cycle approach	Types of projects	Organisation	Network	Communications	Prioritisation and documentation of requirements	Project execution and monitoring of requirements	Test, verification and validation	Results	Output	Software tools and IT support
Other frameworks															
Framework 1 - Kamara et al. (2000)		x	(x)	(x)	(x)		(x)		x	x	(x)				x
Framework 2 - Jeary et al. (2010)		x	x	x	(x)				x	x					(x)
Framework 3 - Vijayamma et al. (2010)		x		x			x			x	x	(x)		x	x
Interviewed construction companies	Offer / role in industry														
Interviewed company 1 Case company (before applying this framework)	POL-2. Single family houses, office buildings, insulation of old buildings, a few types of houses with variants, new development	x	(x)	(x)			x	x	x			(x)		x	(x)
Interviewed company 2	POL-2 and POL-1. "Everything except sky scrapers", mostly new development	x	(x)	x			x		x	x	x	(x)		x	(x)
Interviewed company 3	POL-2. Single family houses, a few types of houses with variants, developer	x	x	x		x	x		x	x	(x)	(x)		x	
Interviewed company 4	POL-2. Single family houses, a few types of houses with variants, developer	x	x	x			x	x	x	x	(x)	(x)		x	
Interviewed company 5	POL-2. Single family houses, a few types of houses with variants	x	x	(x)		x	(x)	(x)	x	(x)	(x)	(x)		x	

Table 1a: An overview of requirements management components in both literature and observed in the construction industry

Interviewed company 6	POL-2. Single family houses, a few types of houses with variants	x	x	(x)			(x)	x	x	x	(x)	(x)		x	
Interviewed company 7	POL-2. Single family houses, a few types of houses, some additional features can be bought	x	x	(x)			(x)		x	(x)	(x)	(x)		x	
Interviewed company 8	POL-2. Single family houses to large housing and office buildings, construction managers, mostly new development	x	x	x		(x)	x	x	x	(x)	(x)	(x)		x	(x)
Interviewed company 9	POL-2 and POL-1. Architects, client advisors, designers, construction managers	x	x	x		(x)	x	x	x	(x)	(x)	(x)	(x)	x	(x)
Interviewed company 10	POL-1. Large hotel, new development	x		(x)			x	x	x	(x)	(x)	(x)		x	
Interviewed company 11	POL-1. Client advisor, large office buildings, streets, energy, environmental, oil, gas, new development	x	x	X		(x)	x	x	x	x	x	(x)	(x)	x	x
Interviewed company 12	POL-1. Client advisor, large office buildings, bridges, highway, metro, new development	x	(x)	X		(x)	x	x	x	x	(x)	(x)	(x)	x	(x)
Interviewed authority 1	POL-2 and POL-1. Authority, often responsible for big public bidding rounds, responsible for many of the buildings in Copenhagen	x	x	X	x	x	x	x	x	x	(x)	(x)	(x)	x	(x)
Legend															
Semi-structured interview															
x = fulfilled															
(x) = partly fulfilled or only fulfilled on a high level															

Table 1b: An overview of requirements management components in both literature and observed in the construction industry – continued

When constructing the framework, Jabareen's (2009) seven point list of main features of conceptual framework models was consulted to ensure that the framework proposed can be correctly classed as a conceptual framework. One purpose of the framework is to help construction firms to overcome their requirements management related shortcomings by providing a high level check-list. Another intention of the requirements management framework is to give project and requirements managers of construction projects a tool for addressing the gap of not having an end-to-end process for handling all their project requirements in a pragmatic way. Therefore the scope of the framework is from the point when the project is started to the point of delivery and project closure. Operations and maintenance are consequently not part of the scope.

The framework consists of 14 core requirements management building blocks (BBs) suitable for the construction domain, each generated from the review and analysis of practice and literature (see section 4). It is recommended to follow the framework from BB1 to BB14 as there is a logical flow around the framework. Nevertheless it is important to note that the building blocks are to be often revisited and dealt with in an iterative fashion. The communications (BB13) and software tools and IT support (BB14) are positioned beneath the other building blocks as they are seen to run in parallel, supporting all other activities.

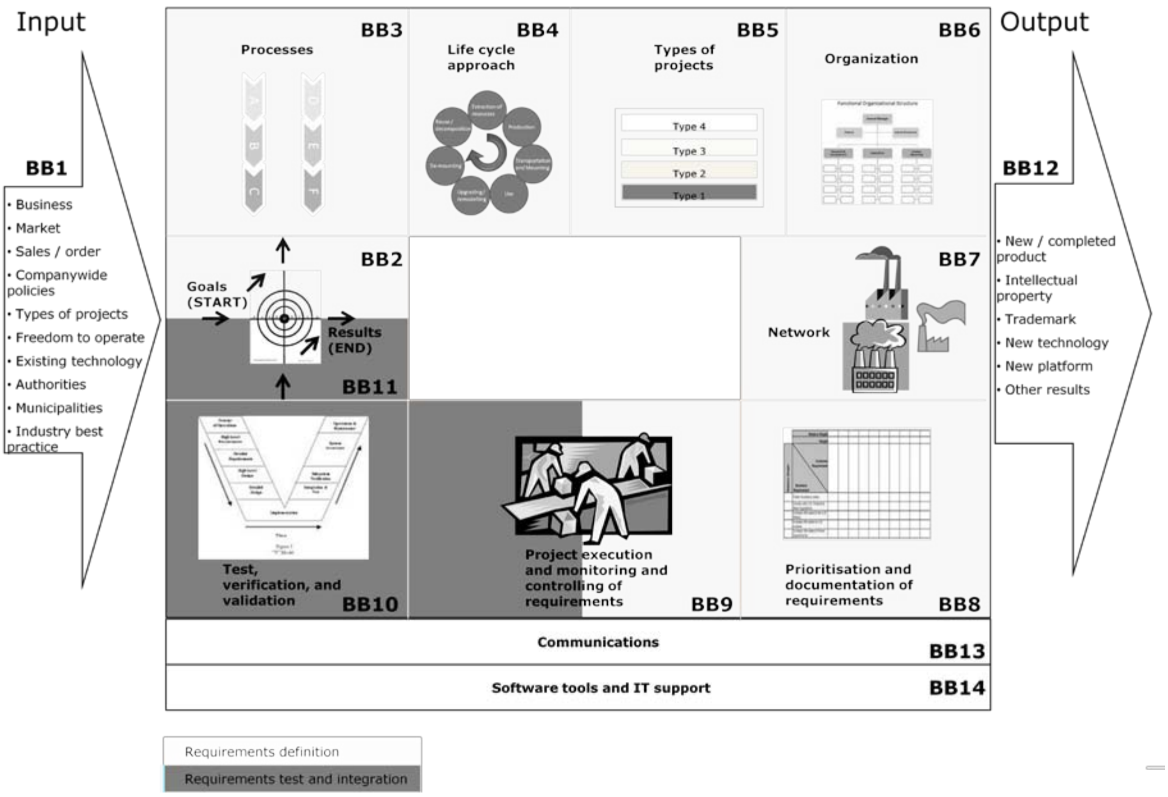

Figure 1: A proposed framework for managing requirements in the construction industry

5.2 BB1: Inputs

The purpose of this building block is to get an overview as early as possible. This is done by identifying the stakeholders that the project team has to consider and by listing all (at this point usually high level) goals and requirements that are already known. Overlooked stakeholders can cause project delays if their requirements come into the project after the planning has been started.

Once all project stakeholders have been identified they can be grouped and prioritised as shown in Figure 2. The requirements of key stakeholders deserve special attention. Usually little energy should be used on requirements coming from peripheral stakeholders.

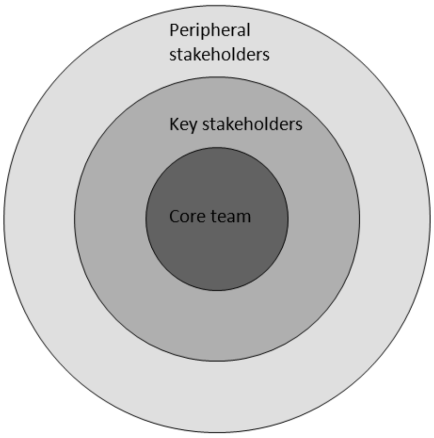

Figure 2: Prioritising the stakeholders of a project

In this building block it is recommended to start categorising requirements and linking them to the already known goals. Useful categories for requirements are:

- Internal or external requirement. This is important as negotiating internal requirements are easier than negotiating requirements from external stakeholders such as authorities.
- Nature of requirements: Mandatory (e.g. laws and regulations), expected (what the customer expects when ordering a product) or positioning (requirements that position the product on the market in relation to other, comparable products).
- Process requirement or physical requirement.
- Authority, financial, technological, industry, organisational, product, societal… requirements.

Categorising requirements in such a way is common practice and helps companies to understand what the project is about and can help to identify contradictory requirements, to prioritise the requirements and manage the progress of how evenly requirements are being fulfilled.

If possible the types of projects that are expected to be run in parallel and the consequences hereof – if it is not a pure construction project – should already be communicated here. Otherwise this is subject to BB5.

5.3 BB2: Goals

If not already done in BB1 a project manager has to be assigned in BB2.

The purpose of this building block is to get a *deeper insight* into what the purpose of the project is and what needs to be achieved by the project. Therefore all high level goals have to be stated here and – where possible – explicitly stated sub-goals should be stated as well. This is a continuation of BB1.

Girmscheid (2010a and 2010b) states that requirements should be mapped to goals. The authors argue that requirements should not exist if there is no goal requiring them. As projects progress goals and requirements often change. Thus mapping requirements to goals is an iterative process. During this building block it is recommended to also define the boundaries and constraints of the project.

5.4 BB3: Processes

The purpose of this building block is to save work by identifying what processes for managing requirements are already available to the project. Are there any processes that can be inherited from e.g. the mother company or similar projects? If a project has several owners it is recommended to agree upon from where the processes (for managing requirements) should be taken. If processes are taken from several sources then somebody needs to be assigned to prioritise, integrate, and further describe those processes.

For a start-up company, process descriptions could be obtained by asking industry associations, looking into standards or requesting support from companies within the start-up company's network. In any case it is important to ask oneself what level of requirements management is needed before starting with the implementation.

5.5 BB4: Life-cycle approach

This building block is needed to get a common understanding of the external context and to avoid surprises. The first question that must be answered is, "what period of time needs to be considered and what are the relevant life-cycle phases?"

The authors propose that there are four different life-cycles that should be considered in construction projects: the life-cycle of a building, the life-cycle of a requirement (see Figure 3), the life-cycle of the project, and the life-cycle of the technology under development. However, the importance of these lifecycles will vary from project to project and resources should be allocated as appropriate.

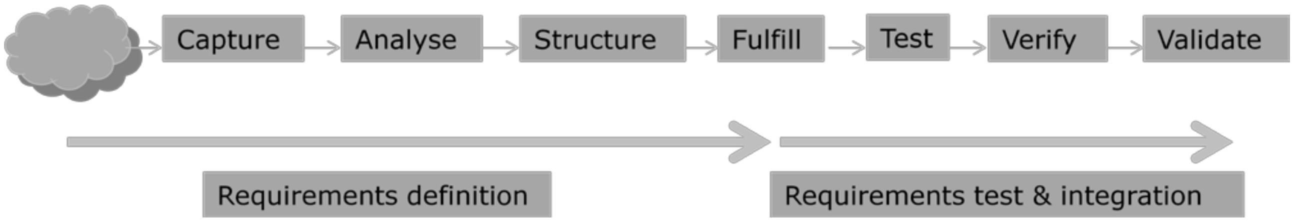

Figure 3: The generic life-cycle of a requirement as encountered in the case project [A description of this life-cycle can be found in Wörösch 2012, page 5]

Once relevant life-cycles have been formulated, the requirements have to be assigned to each phase of those life-cycles. The INCOSE model (2011) is a valuable reference at this stage as it is based on a life-cycle modelling, using its processes will support a life-cycle approach.

5.6 BB5: Different types of projects

What might be declared a construction project is in some cases, as e.g. the case project, a construction project *and* a development project (product, technology, platform, …) of some sort.

When dealing with multiple projects all of them will result in additional requirements that have to be added to the gross list (see section 5.9, BB8) of requirements. Those extra requirements have to be evaluated individually, as they might result in new types of requirements. It is important to catch new types of requirements coming into the project as they might have to be handled differently by the requirements manager and project team compared to already known requirements.

It is worth noting that when it comes to managing requirements the maturity of the staff managing requirements on a building project is often dissimilar compared to staff managing requirements on a development project.

5.7 BB6: Organisation

The organisation of a project plays an important role when managing requirements. The following questions can help to identify requirements management related issues and gaps in an organisation:

- Are sufficient human resources available so that one person can be assigned to each requirement? Each person can have responsibility for several requirements.
- Are those persons from one or several organisations? If human resources come from several organisations then it has to be ensured that all requirements and their respective status' are documented at the same place and that relevant people have access to them regardless of the organisation they come from.
- What is the skill level of those persons? Do they need training in requirements management? What is their organisations' general maturity level when it comes to introducing and following processes? Low skill and maturity levels pose risks to the project.

- Are the relations between people and tasks well defined? This is important when one person is handing over e.g. a work package to another person.
- Are some members of the staff working on several projects? If yes, this could be a constraint as it diverts focus from the projects' requirements.
- Are requirements handled by several people or is there a requirements manager on the project? Should there be one? What happens if there is no requirements manager on the project? For complex, expensive projects it is recommended to use a requirements manager.
- Are there clear rules for how responsibility for requirements should be divided? If no such rules exist it is recommended to make them as this makes the planning process more efficient and helps reducing disagreements within an organisation.

5.8 BB7: Network

The purpose of this building block is to map the network related to the case project. Mapping the network helps to double check that no stakeholder has been forgotten and shows synergies that can be exploited, e.g. staff from companies within the network can sometimes be asked to comment on requirements in certain areas and contribute with their experience.

The idea is that everybody involved, individuals as well as organisations, have provided their input during project planning and that all inputs are checked by experts if necessary.

The mapping of other companies in the network adds another dimension to requirements management as it makes sure that the responsibility for requirements is clearly divided between the different companies and the main responsible for each requirement is identified.

5.9 BB8: Prioritisation and documentation of requirements

In order to get a more complete picture of a project's requirements, a gross list containing all requirements that have been gathered from (key) stakeholders, including companies in the network, has to be made. Once this gross list is finished, it needs a critical examination. The following questions and recommendations are considered to be helpful when streamlining the list:

- Have individual acceptance criteria for all requirements been agreed upon and documented? If not this might cause disagreements later in the project.
- Has a suitable structure for documenting the requirements been identified (Wörösch 2012)?
- In BB1: Input several categories of requirements have been identified. In the present building block it should be checked whether requirements have been added to the different categories as expected. One should react upon gaps.
- Are the users' needs covered?
- Does the sum of requirements make sense? Does it look like some requirements have been forgotten? Has the correct level of ambition been chosen?
- How many levels of requirements (main requirements and sub-requirements) are present in the project? Requirements need to be broken down into meaningful parts.
- Have the requirements been phrased in a way that is easy to understand and unambiguous?

- Are the requirements consistent in phrasing?
- Has terminology been used that can be misunderstood or not understood at all by stakeholders?
- Have duplicates been removed?
- Have synergies been identified?
- Have contradictory requirements been discussed with the stakeholders they originated from? It might not be possible to fulfil all requirements.
- Are all requirements originating from a specification and linked to a goal?
- Have all requirements been prioritised, e.g. “1” is very important, “2” is important and “3” desired. This is helpful when being under time pressure or when having limited resources.
- Is there a unique ID for each requirement? This helps avoiding misunderstandings.
- Have the requirements been grouped and assigned to work packages? This helps identifying synergies and finding owners for requirements.
- Has each requirement been assigned to one owner and at least one project phase?
- This building block lays the foundation for test, verification, and validation (section 5.11). Have plans been made that describe “How to” and on “What level” test, verification, and validation should be done?
- It is recommended to conclude BB8 by making a baseline.

Once the list has been streamlined requirements should be communicated to the project stakeholders.

5.10 BB9: Project execution and monitoring and controlling of requirements

This building block focuses on what happens to requirements during the execution phase of a project.
In this phase it is recommended to monitor and control the status of requirements on a regular basis.
Most projects have a weekly or monthly status reporting. That reporting can be extended to also cover a high level reporting of a project’s requirements status.

The following questions can be advantageous to ask when monitoring requirements:

- Is the progress as planned? On a high level, one can check how many requirements were planned to be incorporated at a certain point of time and compare this number to the actual, achieved number.
- Are some requirements out-dated or not needed anymore?
- Are there any signs of gold plating, i.e. customers getting more than they pay for?
- Have the dependencies between requirements changed due to the altering, updating or addition of requirements? Software tools can help to monitor and track such dependencies.
- Has each requirement been incorporated / completed in adherence with the original definition of the requirement?

- Can testing, verification, and validation already start for some groups of requirements? As can be seen in Figure 1, this building block is on the borderline between requirements definition and requirements testing and integration.

When working in this building block, the authors recommend reference to the PMBOK guide (PMI 2013), which provides a practical description of how to monitor and control the scope of the project.

5.11 BB10: Test, verification, and validation

This phase is usually done before a building is handed over to a customer. As has been revealed during the interviews and literature study, this building block is new in construction but has successfully been applied to other domains using systems engineering. The interviewed companies stated that the testing they undertake is limited. None of the companies interviewed had a structured approach for the verification or validation of requirements.

The most common answer received during the interviews was that standard work descriptions and quality control are being used and the tests that are dictated by authorities are done.

In the "Prioritisation and documentation of requirements" building block it has been recommended that the acceptance criteria for each requirement should be stated when documenting requirements. In the "Test, verification, and validation" building block those acceptance criteria should be used to test against.

Verifying requirements makes sure that requirements have been incorporated in the right way. Validating requirements ensures that the requirements actually meet the users' needs and that the specifications were correct to begin with. When being under time pressure it is advised, at a minimum, to test, verify, and validate priority "1" requirements.

Once the test, verification, and validation of a requirement has been done and the results are satisfactory, the status of this requirement can be considered "Accepted" meaning acceptance criteria are fulfilled. After a formal reporting to the project manager the status can be set to "Finished".

If a test, verification or validation fails, the reason for that has to be found and corrective actions have to be taken. This implies going back to a previous building block of the framework and doing a new iteration of the failed item.

5.12 BB11: Results

Applying the framework for managing requirements should contribute to creating project results. Those results have to be compared to the goals that have been stated at the beginning of the project or the latest, updated version of those goals. Have those goals been achieved? Has the purpose of the project been fulfilled? Have all requirements been incorporated, tested, verified, and validated?

Are the achieved results as expected? If not, then it is necessary to go backwards in the framework and trace the cause of non-performance. Actions have to be taken depending on the cause of non-performance. If the results are as expected, it is recommended to move on to the “Output” building block.

It is advised to re-visit the results building block to gather experiences while working with requirements management, during a lessons learned session at the end of the project.

5.13 BB12: Output

The project has been initiated to create output. In a construction project, the output can be tangible, transferable goods, e.g. a building, product, platform, new technology, or intangible, e.g. intellectual property, a trademark etc. Other results than the ones mentioned here are possible. Output should either be handed over to a customer or back to the mother organisation.

5.14 BB13: Communications

The communications building block has the purpose to ensure the following:

- Regular meetings about the status of requirements are being held.
- Relevant people get access to relevant requirements in the desired format.
- Relevant stakeholders are put in contact with each other.
- The change of requirements and goals is communicated to appropriate stakeholders.
- A regular check of the project teams’ belief to achieve project goals is performed.
- Changes of the project context are communicated. E.g. when new laws are being issued or authority requirements change.
- Organisational changes are communicated as this could mean that the ownership of requirements changes.
- The status of requirements should be prepared for status reports and stage gate meetings.

Please note that communicating is important throughout all building blocks of this framework. Nevertheless it is of particular importance to communicate when prioritising and documenting requirements (BB8).

5.15 BB14: Software tools and IT support

This building block is of supportive nature. To different degrees all building blocks of the framework can be supported by integrated software tools. Tool support is not a requirement for applying the framework but is a tremendous help when the number of requirements is extensive with interdependencies between requirements. The use of web-based tools will be advantageous, especially where teams are not co-located.

6. APPLYING THE REQUIREMENTS MANAGEMENT FRAMEWORK

The requirements management framework described in section 5 was developed and validated whilst researching at a case project. Once the framework was finished it was applied to an additional building project – a test house - to gain further insights into its application. This section describes observations made during the implementation and use of the framework and the subsequent validation of it.

6.1 Description of case company and project

The requirements management framework was implemented within a case project focusing on the development and commercialisation of a new concrete material for building houses and apartment buildings. Despite being in the construction industry, the case company is unique in several ways. Firstly, is very innovative in its sector, constantly developing new technology and products resulting in patents. Secondly, it produces pre-fab sandwich elements and insulation panels from High Performance Concrete (HPC; It is worth noting that when producing HPC sandwich elements much less concrete material is needed resulting in a considerably lower CO2 emission compared to standard concrete material) used to build and energy-renovate houses, and as a consequence it already offers buildings that live up to the European Union's 2020 energy saving requirements (EU 2008), covering the complete value chain. Lastly, it works with product platforms (McGrath (1995) defines the term product platform as a set of subsystems and interfaces that form a common structure from which a stream of related products can be developed and produced efficiently) and elements of mass customisation. This uniqueness is reflected in the structure of the case project that consists of the following four different sub-projects:

1. Technology development used to develop new insulation and HPC material as well as different mounting systems.
2. Product development with the goal to develop new sandwich elements, insulation panels, and jointing in different dimensions.
3. Product platform development of a low-cost, high-end, and insulation panel product platform.
4. Several building projects as e.g. the erection of 40 m2 prototype buildings in Delft, Cape Town, South Africa.

Points one to four (above) deliver and share human and financial resources as well as processes, which simultaneously results in constraints, where 4.) depends on the success of 1.), 2.), and 3.).

The motivation of the case company to use formal requirements management: When interviewing the management team of the case company they realised that some vital processes and guidelines for managing requirements in such a complex set-up were missing and could be of value.

The case company had encountered situations where fire testing of the HPC material had to be repeated due to not being in control of the requirements. When doing serial testing, each failed fire test means a project delay of about two months. Not having an operational process framework for managing, testing, verifying, and validating requirements for each project, also amplified the risk for the case company that they would put faulty sandwich elements on the market. If defective sandwich elements are being built into many houses, it could consequently put the case company out of business once the customers start to ask for compensation. These impending difficulties prompted an in-depth investigation into requirements management and the implementation of an approach recommended by the authors.

6.2 Completeness of the implementation

The requirements management framework was implemented in a case project and a test house building project and observed over the course of two years with the following results:

6.2.1 Implementation on the case project

The implementation of the framework on the case project happened at the speed the different building blocks of the framework were available. The following was achieved during the implementation:

- All stakeholders that the project team had been in relation with had been identified and prioritised. This ensured that important stakeholders could be asked for their requirements in due time and facilitated making a communications plan for the project.
- As a starting point more than 800 requirements had been found, checked for syntax, contradictions, and missing information, prioritised, and assigned to responsible teams and employees.
- The work of the different teams had been divided into work packages which made using synergies and status reporting easier.
- Requirements had been mapped to goals and test cases.
- A suitable requirements structure facilitating a life-cycle approach had been developed (Wörösch 2012).
- Test plans had been made and the test, verification, and validation of requirements had been planned, linked to the risk register and time schedule, and consequently been carried out.
- Key people had been trained in the new processes that were introduced together with the framework.
- The list of requirements was frequently updated. Updating typically happened when the different teams met for discussing the status of the work packages that they were responsible for.
- The implementation of formal requirements management lead to a deeper focus on the alignment between business strategy and requirements.

6.2.2 Implementation on the building project – test house

The implementation of the framework on the test house building project happened once the framework was available in a released version. The following was achieved:

- Each building block of the framework was applied to the test house building project.
- Overall the implementation followed the framework, i.e. first BB1 was implemented, then BB2... With the exception of BB13 and BB14.
- BB13 and BB14 were implemented in parallel to the other building blocks.
- During the implementation of the framework some iterations were done where several building blocks were revisited.
- The individual building blocks of the framework and the framework as a whole made sense during implementation and use.

6.3 Adaptations made to the framework during the case project

When working with the stakeholder requirements definition process several obstacles surfaced: INCOSE's systems engineering model focuses on the realisation of successful *systems*. The focus of the described implementation was on the realisation of successful *projects*. Another obstacle was the fact that the INCOSE model does not give a hands-on description of how to do requirements management. Therefore the PMBOK (2013a) specification has been applied as it is used by most professional project managers world-wide. Furthermore the IEEE standard Std 1233-1996 (IEEE 1996) has been used due to its description of a requirements management process.

After working with the different processes and the project goals for several weeks it became clear that process-wise there was no link between the requirements and goals of the case project. Therefore Girmscheid's (2010a and 2010b) requirements model (Anforderungs-Engineering-Prozessmodell) was used to close this gap as it provides the missing link and is of an iterative nature.

When documenting all requirements of the low cost product platform, not only a table containing all requirements had been made but also a tool called Product Variant Master (Mortensen et al. 2000) had been used to visually describe the platform. This tool has been very helpful for explaining and prioritising requirements.

6.4 Validation of the requirements management framework

The following kinds of validation were done on the requirements management framework:

- The framework was validated on the case project: qualitative validation.
- The framework was validated on the test house building project: both quantitative and qualitative validation.
- An external validation of the framework was done: qualitative validation.

6.4.1 Observations when applying the framework

During the implementation of requirements management and the framework, the project team regularly pin-pointed that this new way of handling requirements was more time and resource consuming than they were used to from similar projects. Nevertheless, after the successful completion of one of the case projects sub-projects the project manager stated that: “If we hadn’t formalised requirements management on the project then managing requirements would have been done in an unstructured way. Often requirements would have been handled by the project members having time for that activity on a particular day. This typically would have meant non-experts handling requirements as experts mostly don’t have any time left.”

This quote emphasises that requirements management did not get any special attention before its formal implementation on the project. This comprised a major risk on the project’s scope, time schedule, and budget. The quote also confirms that formal requirements management as such can be used on projects in the construction industry. There were however, several downsides to the framework observed:

- “Implementing the framework in a project / organisation requires time and resources.” [a team member]
- Project staff have to be educated in using the framework.
- “The different actors have to change their attitude towards requirements management when applying the framework”. [a team member]
- The effect of the individual building blocks on profit and loss is hard to quantify.

When applying the framework to the case company, the benefits could be seen as early as the *Goals* building block. Depending on which team member that had been asked, different answers on what the goals of the project are were given. During this building block, before proceeding further, agreement was reached on the high level goals along with the implementation of the framework and requirements management itself.

During the *Organisation* building block it became clear that some organisational issues had to be rectified. For example, only a few people in the organisation had good product platform skills and sufficient product platform knowledge. This was immediately mitigated by transferring knowledge to other members of the project team. It also became transparent that not enough resources were available for working on all three product platforms at the same time. Often the same people were involved in all three platforms. Therefore the different product platforms were prioritised and interfaces between platforms well defined.

One of the main contributions of the framework was the life-cycle building block, which as one post case interviewee put it: “it *makes visible life-cycle phases that are not covered by requirements*”. When applying the building block it was striking that there were only very few requirements for the last three phases of the building’s life-cycle (see Figure 4).

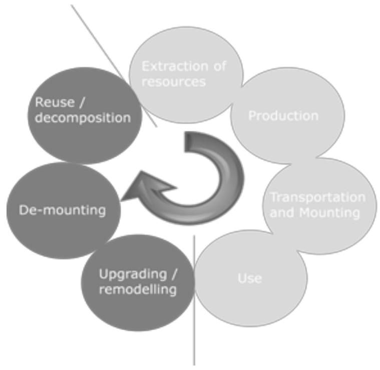

Figure 4: The life-cycle of a building as met in the case project

At the end of the *Test, verification, and validation* building block a check has been done to ensure that all requirements actually had been implemented. This check minimised the risk of project delays due to unfulfilled requirements and quality issues considerably.

During the *Communications* building block the project team discovered that the project goals had been extended since the project had been set off. Now the project team also had to take the requirements for a mobile factory producing high performance concrete sandwich elements into consideration.

Due to the *Software tools and IT support* building block, it was clear that the software solution made a great deal of difference to the stakeholders, as reflected on during one post case interview: "*All requirements, including financial requirements, are documented at the same place. This makes following up on requirements easier and more operational*".

Coming back to the previous example, fire testing of the HPC material, the implementation of requirements management lead to two improvements: 1) It was felt by the project manager that having a clearly defined scope that is aligned with the project time schedule cut off around two weeks per fire test. 2) Being in control of requirements meant that fire tests did not have to be repeated based on requirements management issues and that test results were within the range of what one would expect when looking at the requirements. This also meant that in case of failing a fire test the cause could be found more easily and the exactly same fire test could be repeated any number of times with the same result in the same environment.

6.4.2 Validation on the case project

Several types of qualitative validation were done on the framework:

1) A *theoretical validation* where the standard use of the framework was simulated and then compared to previous building projects of the case company. The outcome of this was very promising.
2) The results obtained when using the framework were *compared to literature*. Here publications from INCOSE (2011a, 2011b, 2012, and 2013) were very helpful from an operational point of view as they give an indication of what results to expect.

3) “*Traces*: The behaviour of specific variables is traced through the model [framework] and through simulations to determine if the behaviour is correct and if necessary accuracy is obtained” (Rykiel, 1996). The traces were done using variables like: management of life-cycle phases, guidance of user to state goals at the beginning of the project, definition of acceptance criteria, comparison of results to goals, consideration of the organizational network and different types of project, effectiveness, usefulness, ...
4) “*Extreme-condition tests*: The model [framework] structure and output should be plausible for extreme or unlikely combinations of factors in the system. This test reveals if behaviour outside of normal operating conditions is bounded in a reasonable manner” (Rykiel, 1996). Several extreme cases were simulated. The most extreme case was running a building project, technology development project, product development project, and product platform development project in parallel.

6.4.3 Validation on the building project – test house

For evaluating the performance of the requirements management framework on the test house building project a comparison of the parameters time and money (most important parameter) was made to two of the case companies previous building projects. The expectation was that the test house building project will perform better in terms of using time and spending money than the two previous building projects it is compared to.

The first building project went for various reasons 300% over time and budget. This was regarded as extreme. But at the same time this was the first project where the case company used the new HPC material. Part of this project was also to get the new material fire safety approved which took several attempts and therefore took much longer than expected.

The second project was delivered in time and had a budget overrun of 30%, which was considerably less than the first project. The requirements management framework was not used on any of those two previous projects.

Concerning the test house building project: On completion of the test house an analysis of the project budget and time schedule showed that the time schedule was kept and the budget was exceeded by 20% even though many more challenges (e.g. the installation of several hundred sensors for measuring different parameters and the exceptionally problematic fitting of the roof) had to be coped with than on the two other building projects.

Comparing those three projects showed a further improvement in the case company’s ability to deliver in time (more robust) and on budget (an additional 10%). Even though the skill to stick to a budget should be improved further. It is hard to exactly quantify how much the requirements management framework has contributed to this improvement. Nevertheless we dare to make the claim that using the framework and focusing on requirements management had a positive influence on the performance of the compared parameters. This claim is supported by project staff and described below.

When asking four selected members of the project staff of the test house building project about the results of applying the framework, the following was stated:

- “The use of the framework puts more focus on requirements management. As the benefit of using it is a better organization of the time available”.
- “Using the framework results in requirements being more structured and divided into work packages. This leads to a faster execution of the project and a clear distribution of responsibilities”.
- “Applying the framework at the beginning of a project gives fewer problems at the end of the project due to requirements management already being applied”.
- “The framework supported a constant update of goals, strategies, and roadmap as the project staff wanted to use requirements management as optimal as possible”.

None of the interviewees said that they would not use the framework again. Three of the interviewees stated that they should have known the framework earlier as this would have helped them in earlier projects. All four interviewed staff considered the framework as a useful help in their work.

When questioning the project manager about the performance of the requirements management framework at the end of the test house building project, he confirmed that the framework as a whole positively contributed to the spending of time and money. He also highlighted that the flow of the framework is aligned with the flow of the project and that the framework had forced some structure into the scope management of the test house project. Altogether he evaluated that the requirements management related challenges of the case company have been mitigated. For completely resolving them more training is needed and the attitude of the staff has further to be improved.

As suggested by the interviewed Danish authority the framework was validated on the test house building project by evaluating a) if the developed framework as a whole was positively contributing to solving challenges concerning requirements management and b) each building block individually and rating it between “+” to “+++” for an improvement in the consumption of time and money, compared to projects where the framework was not used. The ratings “-“ to “---“ were used accordingly where applying the framework led to an increased spending of time and money. Here it is important to distinguish between using the framework for the first time and using the framework on sub-sequent projects. This subjective validation was done by the project manager and some selected key people and is shown in Table 2.

	Expected (Beginning of project)	**Expected (Entire project)**	**Test house (First project)**	**Subsequent projects**
BB1: Input	-	+	+++	+++
BB2: Goals	--	+	+	++
BB3: Processes	+	++	++	++
BB4: Life cycle approach	-	+	+	+
BB5: Types of projects	-	++	+++	+++
BB6: Organization	-	+	+	++
BB7: Network	+	++	++	++
BB8: Prioritization and documentation of requirements	---	--	+++	+++
BB9: Projects execution and monitoring and controlling of requirements	--	-	+	+
BB10: Test, verification, and validation	--	--	+++	+++
BB11: Results	--	-	--	-
BB12: Output	+	++	+++	+++
BB13: Communications	-	-	++	++
BB14: Software tools and IT support	+	+	+	++
Framework as a whole	**-**	**+**	**++**	**++↑**

Table 2: An evaluation of the effect of the individual building blocks of the requirements management framework on the consumption of time and money on the test house building project

The “Expected (Beginning of project)” column reflects the project staffs immediate anticipated effect of the framework and each of its building blocks when the framework was being presented to them. The “Expected (Entire project)” column shows the project staffs theoretical evaluation of the effect of each building block for the entire project once they were thoroughly presented to the complete framework. The “Test house (First project)” column shows the evaluation of the project staff *after* the practical implementation of the framework at the end of the building project. The “Subsequent projects” column reflects their anticipation of the effect of the individual building blocks for subsequent projects. Here they took into account the implementation of some software tools to better support the use of the framework and a learning curve.

When the requirements management framework first was presented to the project staff their response was rather negative as they expected an additional workload resulting in a very little effect. But once they had implemented and used the entire framework they could see that time and money could be saved, the quality of the product and certain processes was improved, and many risks could be mitigated / avoided. After only one project they expressed a strong desire to roll-out the framework for future construction projects.

The application of requirements management at the case company confirmed that

- Requirements management actually can be applied to – at least certain parts of – the construction industry.
- The requirements management framework contributed positively to project results.
- The expected benefits of applying requirements management to the construction industry have materialized.
- The by means of action research and interviews identified shortcomings could be overcome.

6.4.4 External validation of the framework

"Face validity: Knowledgeable people are asked if the model [framework] and its behaviour are reasonable. This test suggests whether the model logic and input-output relationships appear reasonable 'on the face of it' given the model's purpose" (Rykiel, 1996).

Even though the framework had proven to be useful, no claim could be made concerning its generic applicability outside the part of the construction industry that offers pre-defined products. Therefore, to investigate into its general applicability, the framework was upon completion presented to four further construction companies of different sizes. Those companies offer POL-1 or both POL-2 and POL-1 products. The framework was also shown to the technical and environmental department of the city of Copenhagen that, as an authority, is involved in many construction projects.

The feedback received from their industry experts confirmed that the framework helps counteracting the challenges that typically are related to requirements management in the construction projects that are run by them. The industry experts also stated that the framework can be applied to the projects they are typically involved in. At the same time, they all pointed out that it will cost time and money to implement the framework. Nevertheless, the interviewed experts estimated that for large projects (above €10M), applying the framework would result in big savings in terms of both time and money. The savings are expected to be even bigger on POL-1 than projects offering POL-2 products. At the same time, they acknowledged that once the framework has been implemented, future projects will be able to benefit from it and that those benefits will be enhanced when using the framework together with product platforms.

The technical and environmental department of the city of Copenhagen's representatives had the most positive comments of the interviewed parties - "The concept sounds fantastic", "This 'process' facilitates innovation", "It is rare that one sees such a well worked out concept". Since being introduced to the framework, they have begun looking into making this framework obligatory for public tenders. However, it was requested that "the economy (profit / loss) in each building block needs to be quantified. If absolute numbers are not possible then relative numbers will suffice." This quantification was shown in Table 2.

Mishler (1990) defines validation as “the social construction of knowledge.” With this reformulation, the key issue becomes whether the relevant community of scientists and practitioners evaluates reported findings as sufficiently trustworthy to rely on them for their own work. Mishler (1990) argues that for “inquiry-guided research the standard approach to validity assessment (e.g. measuring variations on quantitative dimensions or “testing” the significance of the findings with statistical procedures) is largely irrelevant to our concerns and problems”. As a lot of the described research has been inquiry-based, Mishler is considered to a large extend.

When being asked, in addition to the case company, the authority and two of the companies affirmed that they would use the framework. Following Mishler’s thought the strongest possible validation has been achieved.

7. CONCLUSION

Formal requirements management is necessary in order to improve project reliability in the construction industry. The literature review revealed that there are several elements which are relevant for requirements management, not incorporated into current requirements management frameworks. To be specific, the ‘Life-cycle approach’, the ‘Test, verification and validation’ and a systematised ‘results’ phase and ‘network’ phase are largely missing from the literature. When interviewing and studying companies from the construction industry, it was found that they also lack an approach to cover these important elements. The requirements management framework proposed in this paper, incorporates the best practice for each of the elements or ‘building blocks’ of formal requirements management. In addition, the proposed framework adds the above mentioned missing elements, deemed beneficial for the construction industry. As the framework has an added life-cycle perspective, companies using this framework will find it easier to implement systems engineering at a later stage as big parts of the stakeholder requirements definition process, the verification process, and the validation process based on the INCOSE model (INCOSE 2011) are already being used. It is also believed by the authors that adopting such a framework will help companies to develop and utilise product platforms leading to greater savings and more reliable project delivery.

Qualitative and quantitative validation made it clear that applying formal requirements management through the proposed framework lead to advantages in the case project and as a result, the framework is currently being considered for implementation in several other projects and companies.

Applying the framework to two projects also confirmed that the at the beginning of this article stated goals

- This framework can be used as a tool that allows managers of building projects to manage *all* the requirements they encounter on their projects.
- Furthermore the framework helps overcoming the shortcomings that were identified using action research and during interviews.

were achieved. This means that for the first time formal requirements management and elements of systems engineering were applied to construction projects. This application confirmed the, at the beginning of this study, anticipated positive effects of introducing requirements management to the construction industry.

However, a critical question remains for future research – "when is a project large enough in size to economically justify the use of a requirements management framework (such as the one proposed in this paper)?" Based on the interviews and action research conducted for the purposes of this paper, we recommend that any construction project of over €10M should adopt the full framework. Other future research will entail a cost benefit analysis of each of the building blocks, developing the prescriptive approaches to be used in each building block, conducting further expert interviews also outside Denmark, and doing an in depth validation of the requirement management framework.

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ARTICLE 3 PRODUCT PLATFORM CONSIDERATIONS

Product Platform Considerations on a Project that Develops Sustainable Low-cost Housing for Townships

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Product Platform Considerations on a Project that Develops Sustainable Low-cost Housing for Townships

Michael Wörösch[1], Martin Bonev[2], Niels Henrik Mortensen[3]

Abstract

Construction companies in Denmark are often working with profit margins as little as 1-3% in situations where they deliver high-end buildings to the local market. Even though customers are willing to pay a premium price for high quality, construction companies earn very little on their products. Consequently one Danish company took the decision to produce sustainable low-cost houses and to sell them to developing countries that have township housing programmes. But why would this company believe it could make a profit in the low-cost housing segment abroad, when there is almost no profit in the high-end segment at home? As the research described in this article shows there are three main reasons for their optimism: 1) The successful introduction of a product platform for low-cost houses, 2) a modular approach to the design of low-cost houses, and 3) the application of requirements management as described by INCOSE. 1) to 3) have been studied using action research on a case project.

The case company´s success contributes to people currently living without decent housing by providing insulated, low-cost houses based on the latest technology. The fact that those low-cost houses are solid gives their new owners the possibility to take a loan out on their building which is expected to contribute to more businesses being started up and thereby strengthening the domestic economy. As a consequence of this, additional research is needed in how to further optimise the economy of sustainable low-cost housing based on life cycle considerations. Moreover, it has to be examined how the experience gained can support in maximising the high-end segment in countries like Denmark.

Key words: Low-cost housing, product platform, construction industry, practical implementation, action research

1 Introduction

This section will introduce the trend of population growth and the concept of product platforms which are core to the business opportunity of the research case detailed in this paper.

[1] PhD student; Dept. of Mechanical Engineering; DTU; 2800 Kgs. Lyngby; mwch@mek.dtu.dk.
[2] PhD student; Dept. of Management Engineering; DTU; 2800 Kgs. Lyngby; mbon@dtu.dk.
[3] Professor; Dept. of Mechanical Engineering; DTU; 2800 Kgs. Lyngby; nhm@mek.dtu.dk.

1.1 Population growth in developing countries

It is estimated that about 1.6 billion people around the world live in sub-standard housing and over 100 million are homeless. If no serious action is taken the number of slum dwellers is expected to rise from one billion people today to two billion within the next 30 years (Habitat for Humanity, 2013). This leaves many developing countries with a problem that is hard for them to overcome. South Africa is one of the countries that are taking action, as it tries to solve its housing problem by means of a centrally planned housing programme. Through this programme, since 1994 more than 2.3 million housing units have been made available to nearly 11 million people, where in 2010 alone about 219.000 housing units have been made. The goal for the coming years is to create 220.000 housing units a year. Despite such a tremendous number of erected units, the housing backlog has grown from 1.5 million units in 1994 to 2.1 million units today. This means that 12 million South Africans – a quarter of the population – are still in need of a better shelter (Ministry of national housing and social amenities, 2011).

Inspired by the housing programme of the South African government, the case company described in this article examined whether and how it would be possible to contribute to the housing problem of developing nations with its knowledge and technology. After a careful examination of the National Housing code (2009), the decision was taken to develop a low-cost product platform that could co-exist with both the existing, high-end and re-insulation panel product platforms and to make an offer to the South African housing programme.

1.2 Product platform definition and strategy

The product platform concept has widely been discussed in literature, where accordingly a number of definitions have been introduced by e.g. Muffatto and Roveda (2002). Halman et al. (2009, page 151) for example, refer to McGrath's definition of a product platform: "a set of subsystems and interfaces that form a common structure from which a stream of related products can be effectively developed and produced". The authors base their research on this definition, as it incorporates both the physical and economical aspects of a platform concept. An overview of the product platforms that exist in the case company can be seen in Figure 1.

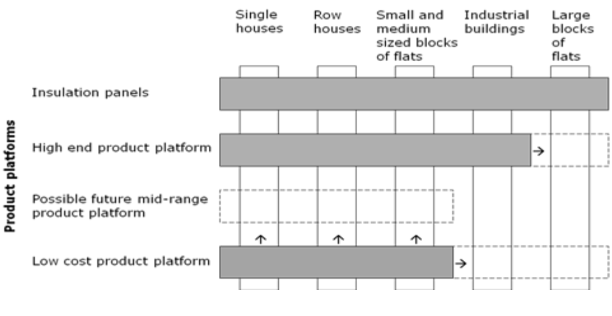

Figure 1: The product platforms that exist in the case company

As illustrated in Figure 1, the insulation panels aim to cover all business segments, while the other two product platforms address only parts of the market, but still keeping the possibility of expanding open. The reasons for believing in the success of a product platform that did not even exist at the time the offer was made were:

- The product platform approach had been rooted in the organisation and the staff of the case company had been trained in product platform thinking for several years
- The successful implementation of requirements management in the case company
- All the desired European safety and product approvals had already been received
- The technology the case company wanted to use had successfully been tried out in several buildings in Denmark (see Figure 2 for an example)
- The senior staff have a long history of successfully executed building projects

The above listed points indicate that a strong base had indeed been established which made it possible for the case company to continue building upon. At the same time the case company was also aware of the main obstacles that had to be overcome. To begin with, the government subsidy for a 40 m^2 stand-alone house only amounts to 55.706 ZAR (= 4.926,87 € using exchange rates from December 25th 2012) (Coetzer, 2010), which is considerably less than what a house based on the high-end product platform costs. Moreover, unskilled labour is to be used, whereas the usual approach of the case company is one of automation and efficiency in combination with a skilled work force. There is also a risk of facing problems using the local building materials with unknown properties and quality. However, the management of the case company had full confidence in being able to produce 40 m^2 low-cost houses at a price that did not exceed the government subsidy. Working with unskilled labour and having to use local building material were treated as risks. Therefore, risk mitigation plans were made for those two points as described in the PMBOK (2008).

Figure 2: A building based on the high-end product platform

Studying the situation resulted in the main hypothesis that creating and introducing a platform concept to low-cost markets would support both, developing countries in overcoming their housing problem in an effective manner, and construction companies to improve their performance in the domestic markets. To this end, this article in particular addresses the following aspects:

a) It is possible and beneficial to develop a low-cost product platform that can be used for making low-cost houses

b) It is possible to make several variants of houses based on that low-cost product platform
c) The new knowledge gained by developing and implementing a product platform for low-cost housing will contribute to improved efficiency and reduced prices in the high-end platform

This paper therefore deals with the question on how to successfully introduce a product platform that supports modularity to the low-cost housing segment of the construction industry. To answer this question, after a literature review (Section 2), an explanation of the applied research and design methods (Section 3) and a description of the case (Section 4) will be provided. Section 5 then gives a brief overview on the key observations that have been made when developing the low-cost product platform and building houses. In Section 6 the thereby achieved results have been analysed. A final conclusion is drawn in Section 7, where the most important findings are summarised and recommendations for future research are given.

2 Literature review

Even though the work on the case project was mainly of a practical nature, a lot of knowledge has been drawn from literature, where both academic publications as well as literature from seasoned practitioners have been consulted. Table 1 below gives an overview showing the main references considered for this article and what they cover in the context of this research:

Table 1: Main literature considered in this research

	Ulrich and Tung (1991)	Thuesen and Hvam (2011)	Mortensen et al. (2008)	Simpson et al. (2011)	INCOSE Systems Engineering Handbook (2011)	Huang et al. (2005)	Roy et al. (2003)	This article
Product platform		X	X	X		X	X	
Product platform in construction		X					X	
Product platform in construction – low-cost housing								X
Product variants / family	X		X	X		X	X	X
Modularization of products	X	X	X			X	X	X
Requirements management					X		X	

The concepts of product modularization (Ulrich and Tung, 1991) and product platforms have extensively been discussed in literature. Huang et al. (2005) for example have studied several companies in different industries using product platforms. In addition, Hvam (2011), Mortensen (2008), and Simpson (2011) provide a number of publications on the application of product platforms, where the approach of using product platforms has mainly been put in the context of consumer electronics, car, aerospace, and software industries. However, at the same time very little theoretical contribution could be found on how to apply product platform principles to the construction industry (Roy et al., 2003). As of today, there are in particular no published attempts to practically implement a product platform which facilitates modularity and product variants for low cost housing in this industry.

3 Research and design methods

The research described in this article makes use of action research (AR) defined by Coughlan and Coghlan (2002) as well as Checkland and Holwell (1998) for creating the needed models and tools. The approach was applied to a case project, where full access to all key people and complete access to all documents relevant to this research, including minutes of meetings in addition to documents containing the future strategy of the case company and its products, existed (Voss et al., 2002 and Yin). In order to cover all parts of the case project's value chain (see Figure 3), including the sub-projects described in Section 4 "Description of case", several interview rounds with key persons from the construction industry and the case project have been conducted.

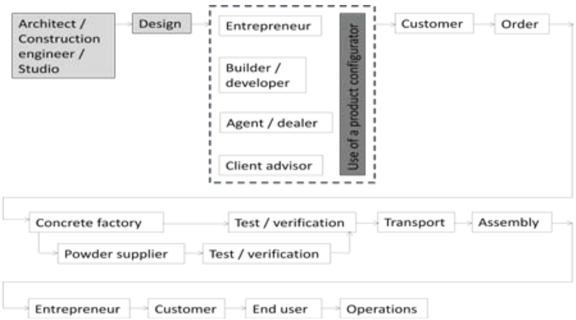

Figure 3: The value chain of the case project

For reasons of comparability and consistency interviews were conducted using a question template from previous research for all participants, resulting in a master document that covered a wide range of different requirements: from functional, non-functional, technical, market and organisational requirements, to requirements towards the project manager and finally to requirements of the stakeholders themselves. This was used to implement requirements management on the case project and was actually (at that time unconsciously) the first step towards a low-cost product platform. During the analysis of the second out of four AR cycles it became clear that requirements management on the case project worked well (Wörösch, 2012), as it significantly contributed to having a clearly defined scope of the case project, its sub-projects, and the different product platforms – the two existing ones as well as the one that needed to be developed.

When linking the requirements of the low-cost product platform to the company and product strategies, modularity of the houses based on this platform could be ensured. In an architectural perspective, a definition of the term modularity that fits well with this research has been described by Ulrich and Tung (1991). The authors refer to "the construction of a building from many instances of standardised components. In manufacturing the term often refers to the use of interchangeable units to create product variants" (Ulrich and Tung (1991, page 73)). Examples of the hereby achieved modularity will be given in Section 6.

4 Description of case

Despite of operating in construction, the case company is unique within its industry in several aspects. Firstly, it produces sandwich elements and insulation panels from High Performance Concrete (HPC) that are used to build and renovate houses to have greater energy efficiencies. Secondly, the company constantly develops new technologies and products resulting in patents. Therefore, already today, it offers buildings that live up to the European Union's 2020 energy saving requirements, covering the complete value chain (see Figure 3), where responsibility is not pushed down to sub contractors. The uniqueness of this case is reflected in the structure of the case project that consists of four different types of sub-projects, which will in the following section be shortly introduced:

5. Technology development used to develop new insulation and HPC material as well as different mounting systems
6. Product development with the goal to develop new sandwich elements, insulation panels, and jointing in different dimensions
7. Development of low-cost, high-end, and insulation panel product platforms
8. New building projects (such as the erection of 40 m^2 prototype buildings in Delft, Cape Town, South Africa)

1) to 4) deliver and share human and financial resources as well as processes, which simultaneously results in constraints, where 4) depends on the success of 1), 2), and 3).

5 Observations

When developing the low-cost product platform and building the houses, a series of key observations, that are further grouped and described in detail, has been made.

5.1 The low-cost product platform

- On a conceptual level there were many elements that could be re-used from the high-end product platform; e.g. the basic methodology when describing a platform structure and how to phrase requirements. Previously, there was not much reuse between the two other product platforms
- A solution for the design of the HPC elements has been found that required only few tools for assembly. Buildings can even be assembled without using power tools, since stable electricity sometimes is absent on some building sites. An assembly where only few tools are needed also makes teaching of staff easier and leaves less room for error
- Even though unskilled labour and no high technology production are being used, many houses can be produced during a year. This is due to the production of only few different kinds of elements, which are strongly standardised and can be used across the product variants. Using unskilled labour and no high technology also changes the description of requirements from being database and specification focused to being expressed in photographs and drawings wherever possible
- Once the HPC elements with their pre-mounted windows and doors are ready for assembly, a Type 1 house (see Figure 4) can be assembled within one working day. This fast assembly also contributes to the possibility of building many Type 1 houses in the course of a year and at the same time it prevents theft or unauthorised occupation, as the houses are closed in the evenings
- The local building materials (about 99%) can be used without any quality problems. The only exception to the use of local material is a special concrete binder that is sent from Denmark. In result, the use of local material creates domestic jobs and reduces CO_2 emission that otherwise would have been caused by transportation from abroad
- The scalability of the low-cost platform is high. This means that when, for example, the production has to be doubled or halved it can be done relatively fast at low cost
- The price of a 40 m^2 stand-alone house (basic model) based on the low-cost product platform does not exceed 55.706 ZAR. This means that the case company can continue building the low-cost houses without generating losses and the housing programme can accordingly achieve its yearly targets

5.2 Modularity

Modularity has been achieved in several facets. For the customers this means that they can upgrade their houses with extra rooms, a veranda or a bigger kitchen at a low price at the time of ordering. Upgrading is possible in all situations where the housing programme facilitates a contribution of the end user. Besides, modularity can also be achieved by using additional means; e.g. by giving the customer or resident the possibility to enhance the house by adding a rainwater collector that gathers rain water from the roof facilitating cultivating a garden for the house. Another benefit of achieving modularity is that it also is possible to improve the houses with solar panels for generating power for hot water, lighting, charging computers, cell phones, and other consumption. Also, here the housing programme has to allow this kind of improvement.

5.3 Knowledge transferred back to the high-end product platform

- The high degree of standardisation contributes to a high throughput in production. The high-end product platform needs to be examined for possibilities to increase standardisation and to get away from the current high level of uneconomic flexibility
- The use of prototype elements, drawings, and verbal explanations instead of lengthy documents has been very successful. This method of controlling the scope for a product platform could also be introduced to the other product platforms, which, however, would mean to go away from a systems engineering best practice approach as described in the INCOSE Systems Engineering Handbook (2011). It has to be examined to what degree this could be done while still maintaining sufficient documentation and living up to described processes
- The rather effective way of teaching new local staff and the team, created a very inspiring feeling during the teaching sessions and should further be applied to staff working on the other platforms as well. Flying the key personnel of the case project to South Africa in order to participate in building low-cost houses could be one way of transferring the new knowledge and a positive team spirit back to Denmark
- This new knowledge gained by developing and implementing a product platform for low-cost housing will contribute to improved efficiency and reduced prices in the high-end platform, as many decisions that had been taken on the high-end product platform have been seriously challenged. An example is the very high focus on the factor cost for the low-cost platform that has never been enforced to such a degree on the high-end product platform

Having summarised the main observations, in the next section the results of implementing a low-cost product platform into the case project are discussed.

6 Discussion of results

By the end of action research cycle two, the research conducted in the case project had given a series of theoretical and practical results. The main results have been listed below.

6.1 High level results of making a low-cost product platform

As anticipated, from a technical and process point of view, it was indeed possible to develop the low-cost product platform and build houses based on it within the estimated time. Due to the active use of requirements management, the scope of the new product platform was clearly defined, while market segment-wise there was no overlapping with the existing product platforms. From a societal point of view, building low-cost houses at high speed helps ensuring that more people have decent housing and thereby producing an increase in quality of life. Furthermore, a relatively fast, cheap and secure assembly, contributes to reducing the large backlog in the low cost housing area. Thus, as demonstrated by the case company, local job opportunities together with relevant education and training are created. This increases the standard of living and improves future chances for personal development. Houses made from HPC are solid and have according to Danish Standard (2001) a minimum life expectancy of 50 years, while in practice concrete companies often calculate with 70 or more years. This is much higher than what most housing objects currently have. This longer life expectancy makes it possible for a house owner to take a loan out on their house, which in turn can contribute to starting up financial businesses and thereby to strengthening the domestic economy.

6.2 Results related to the main hypothesis

6.2.1 The low-cost product platform and the use of modularity

The low-cost product platform currently supports three types of houses, of which two will be explained further in this paper. All houses based on this platform can only be ordered in a light or in a dark version. Each of them comes with two different surface structures, a smooth and a brick-like one. Altogether the customer is offered a limited number of choices, as all concrete elements, windows, doors, materials, sizes, and interfaces are completely standardised. This radical standardisation is the main difference from the high-end product platform, for which more variety and a higher degree of customisation is available. Figures 4 (Type 1) and 5 (Type 2) show two types of 40 m^2 houses, that are based on this new low-cost product platform.

Figures 4 and 5: Two different 40 m^2 buildings made from HPC – Type 1 and Type 2

Modularity on the low-cost product platform exists on two levels. On the element level, the HPC elements are prefabricated and scaled to approximately 1,2m in width. Figure 6 illustrates the conceptual assembly of a Type 1 house based on those elements. On the building level, several variants of the Type 1 and Type 2 house exist. The Type 1 house can be produced as basic 40 m^2 model or as one of four variants, where modules like a veranda or extra rooms can be added. Depending on what modules are added, the size of a Type 1 building can go up to 56 m^2, as depicted in Figure 7.

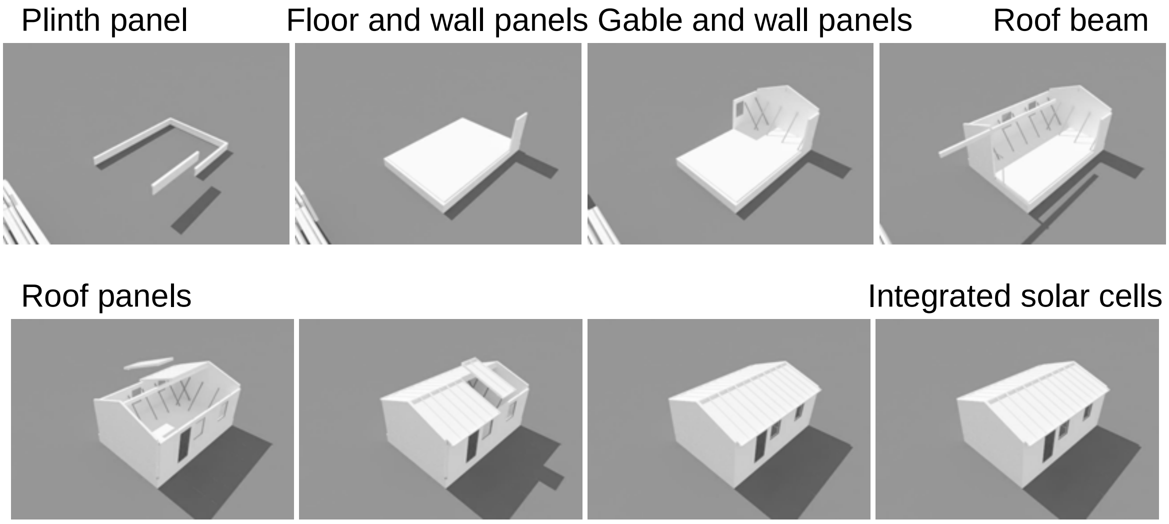

Figure 6: A Type 1 house assembled from prefabricated HPC elements

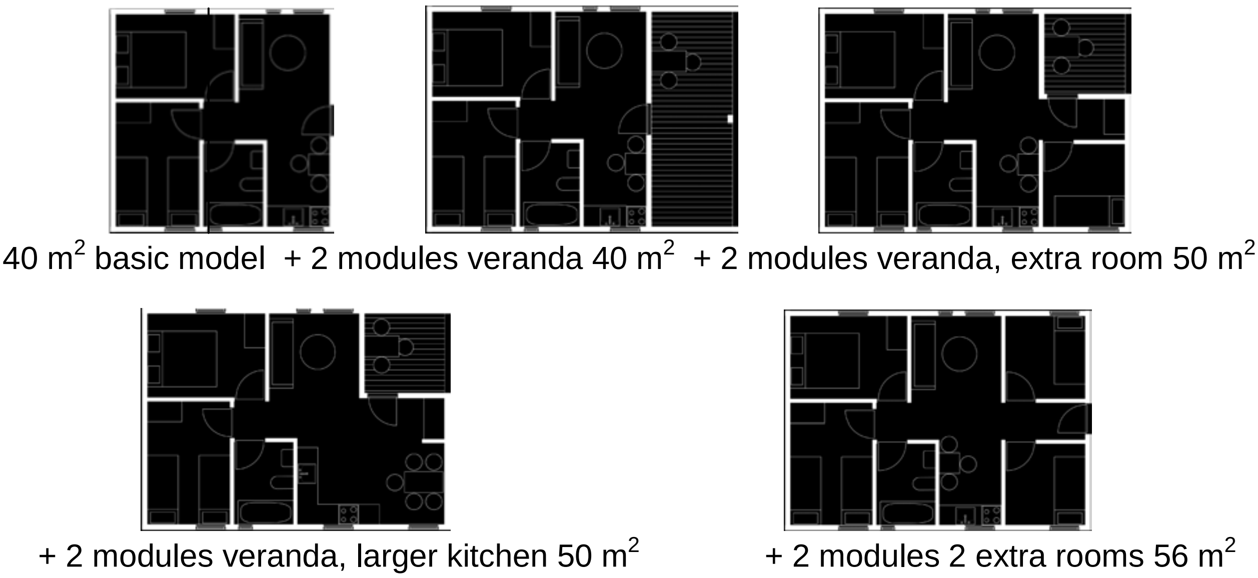

Figure 7: The five variants of the Type 1 house (Figures 6 and 7 have been taken from a sales offer to the South African Housing Programme)

6.2.2 Knowledge transferred back to the high-end platform

A lot of knowledge has been gained when making the low-cost product platform. Some of the key learning points were:

- Even though there were only a few choices the customers could make, when ordering a house, the offered variety appeared to be suitable for this market segment. This will result in a review of the high-end product platform, to ensure that customers are not offered an infinite degree of variety and that the financial contribution per variant is high enough. Non-profitable variants should be removed from the platform
- Starting the low-cost product platform from scratch, rather than trying to take the high-end product platform as a starting point for scraping off layers, turned out to be the right decision. In hindsight, it is our belief, that it would not have been possible within the given timeframe to achieve the cost goal per unit using this approach
- This was the third product platform the case company developed. Since the high-end and insulation panel product platforms were well defined and linked to the company strategy, developing a third product platform took considerably less time. The experienced staff and the right software tool support, such as the use of product configuration systems (Bonev and Hvam, 2012), contributed strongly to the fast development of this platform

7 Conclusion

In this article it has been described how a low-cost product platform has successfully been developed and implemented in the low-cost housing segment within the construction industry. The houses based on this platform are built up in a modular approach, where modularity has been achieved both on element and on building level, resulting in buildings which can be delivered in several types and variants. The main difference compared to a coexisting high-end product platform is the high degree of standardisation and the limited number of commercial variants, which has been adapted according to the requirements of this market segment. Besides, the application of requirements management as described by INCOSE has resulted in working descriptions containing much less text, but with more pictures and drawings instead. This positive attempt to use product platforms in the low-cost segment of the construction industry confirmed the main hypothesis of this research (Section 1) and shows that the product platform approach is a valid strategy for meeting the low cost housing demand of developing countries. Hopefully the described case inspires other construction companies to introduce a product platform concept for their products.

Despite the promising results, further research is needed in the following vicinities: Since there is a high need for decent housing, smart solutions have to be found for quickly producing a high amount of houses, which are cheap and long lasting. If companies find a way of addressing this issue in a profitable manner, they are more likely to participate in this enormous task. At the same time it is important that the applied housing solutions are sustainable, as according to EU, 2010, residential and commercial buildings are responsible for about 40% of the total energy consumption and 36% of the total CO_2 emission in the European Union. Other parts of the world will soon face similar situations to those described above, if there is no sufficient focus on sustainability when producing such a vast amount of buildings. To this end, further research is needed in how product platforms, by means of effective development and production, can further contribute to the low-cost housing segment and to the construction industry in general. Finally, it is necessary to further optimise the economy of sustainable low-cost housing based on life cycle considerations. Once this has been done, it has to be examined how the gained experience can support in maximising the high-end segment in countries like Denmark.

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ARTICLE 4 PRODUCT MODELING METHODS

Extending Product Modeling Methods for Integrated Product Development

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EXTENDING PRODUCT MODELING METHODS FOR INTEGRATED PRODUCT DEVELOPMENT

Bonev, Martin; Wörösch, Michael; Hauksdóttir, Dagný; Hvam, Lars

Technical University of Denmark

Abstract

Despite great efforts within the modeling domain, the majority of methods often address the uncommon design situation of an original product development. However, studies illustrate that development tasks are predominantly related to redesigning, improving, and extending already existing products. Updated design requirements have then to be made explicit and mapped against the existing product architecture. In this paper, existing methods are adapted and extended through linking updated requirements to suitable product models. By combining several established modeling techniques, such as the DSM and PVM methods, in a presented Product Requirement Development model some of the individual drawbacks of each method could be overcome. Based on the UML standard, the model enables the representation of complex hierarchical relationships in a generic product model. At the same time it uses matrix-based models to link and evaluate updated requirements to several levels of the product architecture and to illustrate how these requirements have an upstream (towards stakeholders) and downstream (towards production) effect on the product architecture.

Keywords: Product Modeling, Requirements, Integrated Product Development, Product architecture, Product Variant Master

1 INTRODUCTION

1.1 BACKGROUND

In today's global market competition, manufacturing companies are forced to keep up quickly with a dynamically changing competitive environment. Launching innovative products in accelerating development cycles becomes a crucial competitive advantage (Meyer & Marion, 2012). In order to achieve a high productivity in their product development (PD) process, firms are under pressure to employ suitable tools and methods, which allow an in-depth understanding and managing of knowledge related to the products, processes, but also to the project environment (Cooper & Edgett, 2008). To this end, both researchers and practitioners have put much effort in developing structured approaches on how to make the process of PD more efficient and thereby to reduce the development time and accomplish more successful results. Standardized procedures, methods and notations have been introduced, aiming at improving the management and collaboration of product development projects. Pahl & Beitz (2007) and especially the VDI-Guidelines 2221-2222 e.g. describe a stepwise procedure for product development, starting from identifying the design requirements to modeling the detailed design. The design process is hereby divided into individual steps, which can partly be performed in parallel (Simultaneous Engineering), while keeping a close contact to customers and suppliers. Similarly, Ulrich and Eppinger (2012, p. 2) define product development as a "set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product". Traditionally, these phases are performed separately and sequential, except for the detailed design step, which usually includes a number of internal iterations (Unger and Eppinger, 2011). In Concurrent Engineering (CE) all requirements products need to satisfy throughout their life cycle are captured already in the planning and concept phases. Since the majority of the cost is determined at this early stage of the design process (Whitney, 1988), having an overview of the complete lifecycle of a product may reduce all related cost from purchasing to product delivery significantly (Anderson, 2003). Accordingly, the Quality Function Deployment (QFD) and the Design Structure Matrix (DSM) have widely been utilized to identify customers' needs and to link them into the created product architecture (Vezzetti et al., 2011).

1.2 RESEARCH PROBLEM AND OBJECTIVES

Despite the great efforts within the modeling domain, the majority of methods described in academia typically address the uncommon design situation of an original product development of a single product, where the degree of design freedom remains rather high and solutions can be created independently from current product portfolios and product families. At the same time, studies illustrate that 70-90% of the development tasks are related to redesigning, improving, and extending already existing products (Encanação et al., 1990; Ullman, 1997). Existing design specifications are thereby adapted to satisfy new design objectives and constraints (Fowler, 1996). In addition, product development projects are yet increasingly dealing with rising product complexity (Malmquist, 2002). It has therefore become crucial not only to consider internal relations of the product structure (Eppinger et al., 1994; Lindemann et al., 2009), but also to include a number of different business aspects, such as mass customization strategies (Pine, 1993) and the use of commonality and product platforms (Meyer and Lehnerd, 2011).

To overcome these objections, this research attempts to further develop current modeling methods and techniques, to better meet challenges of designers. By considering up-to-date research and trends, the various aspects of an integrated PD, i.e. activities related to market, product and process are discussed (Andreasen and Hein, 1987). Existing methods are adapted and extended through linking updated requirements to suitable product models, capable of illustrating their effect on both the present engineering solutions and on the physical product and process structure.

2 METHODOLOGY

The presented study follows an action research (AR) approach defined by Coughlan & Coghlan (2002). Based on an initial literature review, this paper discusses current challenges and trends of modern PD projects, while particular attention is paid to the established methods and techniques that aim at addressing these challenges. A conceptual model is subsequently proposed, for better integrating upcoming requirements to the product development process. The model is finally tested and verified based on an industrial case. The collaborating partner is a consortium of five Danish companies and five research institutes, focusing on the development, production, and construction of pre-fabricated High Performance Concrete elements. Even though the organization is profit oriented, like most other companies, it has acknowledged the necessity to do upfront research in related areas in order to move the construction industry forward. Thus a rather innovative product development project has been initiated to create modular building components, that are based on platforms and which correspond to today's requirements. The industrial collaboration is realized through a mixed methods research, in particular through a qualitative dominant research with a sequential time order decision.

3 LITERATURE REVIEW

3.1 KNOWLEDGE REPRESENTATION IN COLLABORATIVE PRODUCT DEVELOPMENT

In today's PD projects there is a growing communication concern to be handled. As a majority of the projects are being performed by working in teams, who frequently work geographically and temporarily independent from each other, related tasks have to be coordinated (Rodriguez and Al-Ashaab, 2004). An important implication of organizing collaborative product development is to be able to answer the question how a design change in redesign will affect the system, either organizational, product or process related (Tang et al, 2010). Traditionally knowledge about partial design solutions relied on the implicit knowledge and experience of individual design engineers (Suh, 2001). To keep up with the competitive environment, it has become important to make relevant knowledge explicit, thus available and shareable to all the parties involved in the development process. Companies which are able to integrate closely the various perspectives of the technical PD together with the required knowledge management will succeed in creating better products in shorter lead times. Product knowledge should represent the product features, their relation to the product components and the way how the created solution meets the marketing strategy. Process knowledge is about the involved business processes, the responsibilities and their interfaces towards supportive technologies. Eventually, project knowledge specifies the resources available, the functional and non-functional requirements, budgets, targets, milestones, and the like (Ebert and De Man, 2008). The implementation of adequate IT systems, such as Product Life Cycle Management (PLM) systems, hereby facilitates the efficient exchange and sharing of relevant knowledge (Vezzetti et al., 2011).
The discussed research demonstrates how much modern PD projects rely on adequate and explicit knowledge representation. The following sections investigate how this knowledge is outlined by related modeling methods.

3.2 METHODS FOR ANALYZING PRODUCT DEVELOPMENT AND DESIGN ACTIVITIES

3.2.1 REQUIREMENTS MANAGEMENT

At the heart of any engineering discipline is the interplay between problem and solution domains (Chen et al, 2013). A requirement specifies what the product must do or defines a quality that the product must have (Robertson and Robertson, 2013). Compelling economic arguments justify why an early understanding of stakeholder' requirements lead to systems that better satisfy their expectations (Nuseibeh, 2001). Requirements Management (RM) proposes methods to cope with the requirements at the early phases of the development life cycle. It presents concepts of identifying, collecting, and allocating "system functions, attributes, interfaces, and verification methods that a system must meet including customer, derived (internal), and specialty engineering needs" (Stevens and Martin, 1995, p.11). On the one hand RM consists of soft processes focusing more on people than products. This characterizes at the requirement elicitation process where requirements are discovered and the main objectives are about understanding stakeholders and discovering needs. When the problem domain is sufficiently well defined, on the other hand harder and more definite modeling techniques can take over (Alexander and Beus-Dukic, 2009). Since detailed descriptions for the requirement specification are typically created in various text based documents of considerable length, it can be difficult to get a sufficient overview of the requirements.

In RM requirements are typically grouped and graded according to their nature, e.g. implied or derived, and the impact the stakeholders have on them (DeFoe, 1993). Investigations on RM challenges have been reported repeatedly over the past years (Juristo et al., 2002). Requirements presentation, as well as incomplete and changing requirements and specifications are thereby seen as a major obstacle that needs to be overcome (Weber and Weisbrod, 2003). The process of moving between the problem world and the solution world is furthermore still not well recognized. Typically the effectiveness of a solution is determined with respect to a defined problem, however, the nature of the problem and its scope could depend on what solutions already exist or what solutions are plausible and cost-effective (Chen et al., 2013). Recent models suggest that instead of doing RM only at the early phases, requirements definition and design are interactive activities, handled simultaneously through the development life cycle (Nuseibeh, 2001). RM therefore concerns much more than a list of "shall statements". Instead in modern approaches RM issues are engineered, involving tools, modeling, database design, customization with scripts, training, and data handling (Alexander and Beus-Dukic, 2009).

3.2.2 MATRIX-BASED MODELING METHODS

Generally speaking, matrix-based modeling techniques help to classify the product structure, i.e. the relationship between elements. Through Quality Function Deployment (QFD) and the Axiomatic Design (AD) method designers can use a series of inter-domain matrixes (Malmquist, 2002) to transfer the requirements (the voice of customer) into specific product attributes, engineering characteristics, possible design solutions and manufacturing activities (Akao, 1990; Suh, 2001). Both methods provide guidelines for designers to make technical decisions more systematically (Hung et al., 2008; Jin and Lu, 1998), with the objective to design customer satisfaction and quality assurance into the product prior to production (Guinta and Traizler, 1993). Successfully implemented, such modeling methods have e.g. helped to increase competitiveness, lower start-up cost, and shorten design cycles (Kovach et al., 2007; Vallhagen, 1996). Further analytical

techniques, such as the Design Structure Matrix (DSM) (Steward, 1981), have been developed to assess, reorganize, and cluster relationships between elements (Eppinger et al., 1994). In order to improve the analytical capabilities, the DSM method has since its introduction been further extended, modified, and integrated into other matrix-based approaches, such as the previously described QFD and AD methods (Guenov and Barker, 2005; Hung et al., 2008). From a solely inter-domain matrix with a limited capability of representing the nature of the relationships, over time the DSM method has increasingly been used on various intra-domain problems, namely in form of a Domain Mapping Matrix (DMM) (Browning, 2012), and in combination with fuzzy logic methods (Ko, 2010). Such DSM tools have been used from reorganizing static and time-based relationships (Browning, 2001) to support planning and scheduling activities (Shi and Blomquist, 2012).
In sum, RM methods – combined with matrix-based modeling techniques – are strong in handling the evaluation of customer driven requirements and a vast amount of static and time-based relations. As long as the relations are described on the same level of abstraction and the information flow goes from the customer domain to the process domain (Suh, 2001), the methods obtain powerful analytical qualities. However, the drawback of such techniques is that they hardly support platform design and product redesign (Malmquist, 2002; Simpson et al., 2010), which is, as previously discussed, a prerequisite for today's product development. The following two sections discuss briefly current approaches within these two domains.

3.2.3 MODELING METHODS FOR PLATFORM-BASED PRODUCT DEVELOPEMENT

In mass customization, product specification processes consist of developing the needed specifications to deliver a customer specific product (Hvam et al., 2008). In this area great results have been achieved where customer needs are transformed directly into product designs and production specifications (Pine, 1993). When pursuing mass customization strategies, manufacturers aim at rationalizing their PD through implementing product family architecture based on product platforms (Jiao and Tseng, 1999). In this context, a product platform can be defined as a "set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" (Meyer and Lehnerd, 2011). Companies implementing platform strategies may among other things reuse parts, assemblies, technologies, concepts, and knowledge while simultaneously reducing unwanted complexity and improving their business potential (Andreasen et al., 2001).
While modeling product family architectures, different phases of the product development have to be integrated with the complying business functions. The formulation of a platform model involves considerations from several perspectives, the so called views. In the functional or customer view, the functionality of the product is first determined. The technical or engineering view then reveals how the functionality is provided and what technology has been applied. The physical view consequently describes how the product design is realized by the physical components (Jiao et al., 2007). In addition, to be able to access supply chain considerations, a supplementary representation of possible production layouts (production view) is needed (Mortensen et al., 2008). In order to be able to incorporate the different views of a product, generic modeling notations have to be applied that enable the representation of commonality, alternative variety, and ranges (Jiao and Tseng, 1999; Harlou, 2006). Such a generic modeling approach has for instance been pursued by Harlou (2006). The different perspectives and relationships are modeled with the Product Family Master Plan (PFMP) technique, also referred to as a Product Variant Master (PVM) (Mortensen et al., 2000). The method is based on the product architecture definition by Ulrich (1995), the theory of technical systems by Hubka and Eder (1988), and the theory of domains by Andreasen and Hein

(1987). Similar to functional modeling (Jiao and Tseng, 1999), by following the basic principles of object oriented modeling, such as generalization, aggregation and association, the PVM technique uses the Unified Modeling Language (UML) standard to create a comprehensive overview of a product architecture (Hvam et al., 2008). With its additional notation, the method shows its advantages in modeling product platform and family architectures.
However, since relationships between elements are mapped only through direct connections (arrows) and constrains (for configuration), when linking all relations of complex products across the different views, the desired overview can no longer be provided. Hence, in the context of relationship handling, the PVM method does not seem to be capable in replacing the strong analytical techniques of a matrix-based model.

3.2.4 PRODUCT REDESIGN AND PRODUCT LINE ENGINEERING

As discussed previously, development projects are rarely original, but are rather based on already existing products and technologies, which can sometimes be a group of similar products or defined as a product family (Smith, 2012). This means that a part of the development artifacts are new and a part of them already exists. For this type of development to be successful, it is therefore essential to be able to reuse as much as possible of the existing artifacts and to understand the relationship between the artifacts in each process step, e.g. requirements, design solutions, tests and processes (Shirley, 1990). Development projects can furthermore be technical, where new innovative solutions are first introduced for general applications and later to be used in actual products. In the case of internal projects, a common objective is to improve existing product structures and design solutions. From this end it is important to understand the upstream traces regarding how new solutions and designs affect the stakeholders (McGrath and McMillan, 2000).
The software society has addressed this issue by methods of Product Line Engineering (PLE) (Rabiser and Dhungana, 2007). In PLE the development process is split into two activities; (1) domain engineering, where the reusable asset is developed and (2) application engineering, where products are developed from the reusable asset in combination with fulfilling new requirements (Pohl et al., 2005). However, also PLE engineering research has reported that further studies are needed in application requirements engineering and in analyzing the relationship between requirements and the solutions (Rabiser and Dhungana, 2007). To facilitate research in RM and PD based on product families, inspired by the development approach of software, as in PLE, the following section introduces an extended modeling method based on the PVM. The method aims at combining the different techniques into one consistent framework and thus to benefit from their individual advantages.

4 PRODUCT REQUIREMENTS DEVELOPMENT MODEL

4.1 INTRODUCING THE PRD MODEL

When assessing the development task of a physical product from a redesign perspective, separately considered, each of the above described methods reveals a strong weakness in providing the essential overview and insight of requirements coming from different stakeholders and their effect on the product architecture. Supportive methods should be able to describe how the customers' requirements are realized, what engineering solutions have to be used, what is the physical structure of the products, and how are these produced. Since it is in particular important to make visual not only which, but also how parts are related, connected or assembled, hierarchical relationships and attributes have to be considered as well. Consequently, the presented Product Requirements

Development (PRD) model builds on the existing capabilities of the PVM technique in mapping the stakeholder´s needs to design solutions. Based on an industrial case, the method addresses both, (1) how complex hierarchical relationships can be mapped and (2) how in turn a resulting product design may affect the stakeholders.

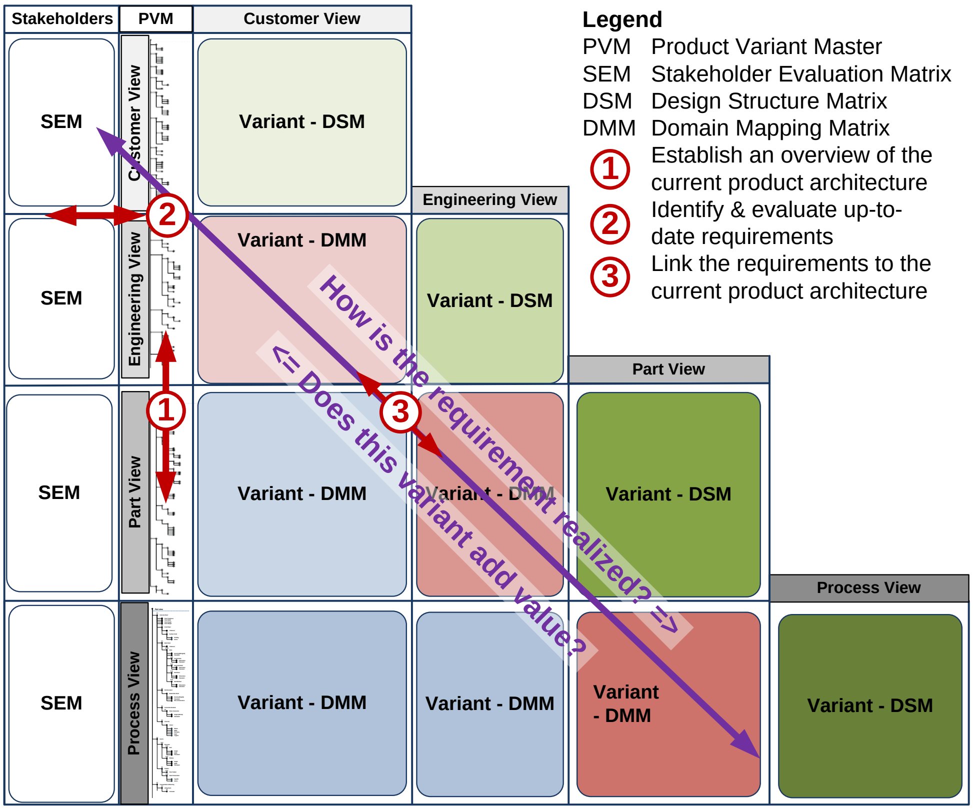

Figure 1 Product Requirements Development Model – Overview

A major difference between the product specification process in mass customization and the development of a new product in a product family is that the first one should fulfill the specific need of a single customer based on available solutions. The latter case needs to consider several stakeholders simultaneously, the impact of new requirements on the product architecture and the effort needed to realize the solutions are unknown. Here, the requirements from each stakeholder have to be evaluated in depth, as they need to be challenged, transformed, and tested by the designers. Since updated requirements have to be set in relation to the current product portfolio, it is eventually inevitable to have suitable models showing the existing product architecture in place. As illustrated in Figure 1, following the notation of the PVM technique, first, if not already available, a generic model of the product family at hand is created. With an additional "Process View", life cycle considerations related to production, transportation and assembly can be included.
Next, similar to the QFD method, in a second step current stakeholder requirements are identified and directly modeled within the existing hierarchical product architecture of the PVM. As indicated in Figure 1, such requirements can appear in the different perspectives (views) of the model. The most common ones are typically driven by the market and are to be placed within the Customer View of the model. Technology driven requirements on the other hand are mapped in the Engineering View. Besides, requirements coming from other domains can potentially be mapped in the corresponding views. On the left side of the PVM, in the Stakeholder Evaluation Matrixes

(SEMs), the requirements are graded and prioritized across the views according to their importance from 1 (low) to 5 (high).
The right-hand side of the PVM displays both, the downstream and upstream impact relationships. Complementary to the DSM and DMM technique, the effect of the requirements on other customer attributes, engineering solutions, physical parts, and processes can be mapped through inter-domain (Variant DSM) and intra-domain matrixes (Variant DMM). The difference to the well-known DSM technique hereby is that each side of the matrix is linked to the PVM structure, and therefore allows a concise expression of hierarchies and relationships, e.g. part-of or kind-of structures and attributes (Hvam et al., 2008). Alternatively, to link hierarchies, variants and attributes with each other using standard matrix-based modeling methods, for each of the seen “Variant DSMs” or “Variant DMMs” a huge number of DSMs or DMMs is needed. Thus in order to obtain the overview of the resulting changes, at this point integrating the PVM technique with the DSM method appears to be beneficial. Having described the principal makeup of the PDM model, in the following paragraph the model will exemplary be applied on the case study.

4.2 APPLYING THE PRD MODEL

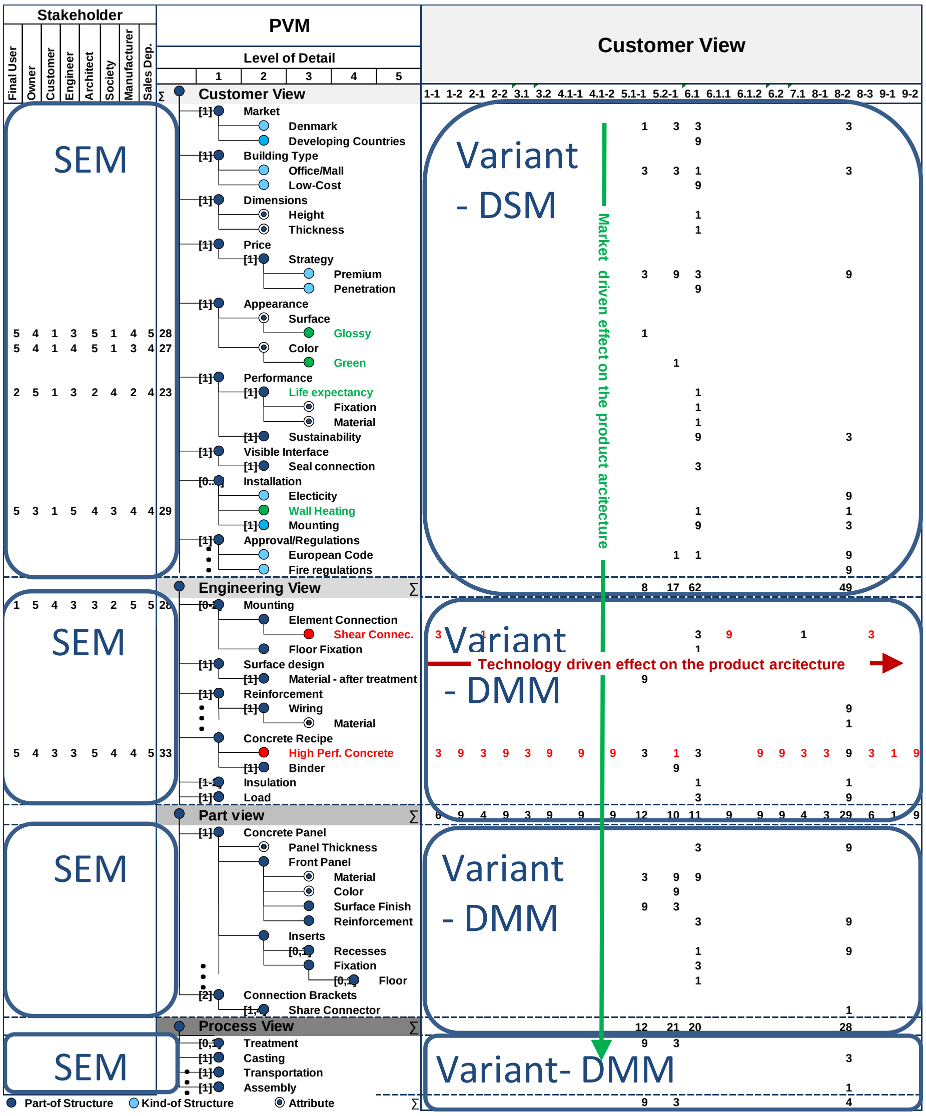

Figure 2 Requirements Evaluation

In the case example first (Step 1) a PVM model of high performance concrete sandwich elements has been created. Figure 2 illustrates a small segment of the entire model, where in Step 2 upcoming requirements were modeled directly into the established PVM. Market driven requirements were illustrated in “green” in the Customer View of the PVM. Here they e.g. concern a new surface and color for the concrete panels, as well as a different heating solution. Besides the requirements from the market, in technological development projects, requirements could also be triggered by the used technical solution as indicated by the “red words” on the engineering level (Engineering View). With the use of the different colors, change requests in the model could quickly be retrieved. Next, on the left-hand side of the PVM the stakeholders of the project were mapped into the described SEMs. In order to formally prioritize their preferences for all new requirements, their individual assessment was aggregated to the sum at the right-hand side of each SEM. Since in the case study all stakeholders had the same relative importance, no other proportional weighting for prioritizing the requirements was needed. It should be noted that in other cases different prioritizing strategies may exist. In some projects stakeholders may either have a greater voting right than others or other rather strategic aspects might be more important. Either way, at the end of this step arising requirements should be given a relative priority.

In Step 3, as illustrated on the right-hand side of the PVM, the impact of the requirements was modeled according to the fuzzy logic model. By grading the strength of the relationships with numbers (1, 3, and 9) (Ko, 2010), again it was possible to formalize how strong the effect of each requirement is on the current product architecture. Rather than only showing if there is a relationship at all, a higher number indicated a stronger effect. Equivalent to the active and passive sum of a matrix (Lindemann et al., 2009), for each Variant DSM or DMM, the total impact of each requirement was calculated at the bottom as the sum of the individual relationships. However, in order to obtain the overview, Figure 2 shows only partly the downstream effects of the requirements. For example, the impact on the stakeholders from the new “High Performance Concrete” (HPC) is depicted through the PVM structure of model. It has both a relatively high priority in the SEM and strongly affects the entire product architecture. “Life expectancy” on the other hand has been less prioritized by the stakeholders. Even though it has a significant effect in the Variant DSM in the Customer View, downstream traces (shown through the Variant DMMs) are less impaired. Another example shows how even more detailed requirements, such as the new “shear connection” can directly be shown within the model. Since “shear connection” is a part-of the mounting group, its indirect effect on a higher level of detail can be seen. In relation to the other requirements, it had a moderate priority from the stakeholders. But since it is not directly visible to the end users and affects a rather limited number of physical components, its impact on the remaining architecture is narrowed. All in all, by integrating the different modeling methods, this method shows how requirements have been graded by the stakeholders (upstream effects) and how they in turn affect the product architecture (downstream effects).

5 CONCLUSION AND FURTHER WORK

Product models, capable of representing how updated customer requirements affect the product lifecycle, enable designers to preserve the overview of the current product architecture, to better coordinate upcoming development activities, and moreover to plan and to calculate alternative solutions. By making use of established product modeling methods, such as the UML-based PVM, this paper contributes to an integrated PD process, which aims at better responding to the requirements of modern product development. Through the integration of several modeling techniques, the presented PRD model overcomes some of their individual drawbacks, e.g. the representation of hierarchical levels, product variants and attributes, while still being able to visualize correlations. Therefore, with the right integration, the PRD model expands the individual modeling possibilities. In sum, it (1) enables the representation of complex hierarchical relationships in a generic product model, (2) links and evaluates updated requirements to several levels of the product architecture, and (3) illustrates how these requirements have an upstream (towards stakeholders) and downstream (towards production) effect on the product architecture. However, in order to address all subsequent aspects of the PD process and therewith to explore the full potential of the model, further research needs to be done. It would for instance be interesting to investigate how matrix-based analysis methods, such as partitioning, could be solved with the Variant-DSMs and – DMMs of the model. Here, future research could for instance focus on what impact structural improvement of the product, through e.g. modularization, could have on the entire product architecture as well as on new requirements.

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ARTICLE 5 PLM SYSTEM SUPPORT FOR MODULAR PRODUCT DEVELOPMENT

PLM System Support for Modular Product Development

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PLM SYSTEM SUPPORT FOR MODULAR PRODUCT DEVELOPMENT

Hans Peter Lomholt Bruun[1*], Niels Henrik Mortensen[1], Ulf Harlou[2], Michael Wörösch[1], Mikkel Proschowsky[2]

[1] *Department of Mechanical Engineering, Technical University of Denmark, Building 426, 2800 Kgs. Lyngby, Denmark*
[2] *Center for Product Customization, Technical University of Denmark, Building 371, 2800 Kgs. Lyngby, Denmark*

1. Abstract
A modular design strategy both enables, but also demands, parallelism in design activities and collaboration between a diversity of disciplines in companies, which often involves supporting computer-based tools for enhancing interaction, design management, and communication. Product Data Management (PDM) and Product Lifecycle Management (PLM) systems offer support by automating and managing some of the operational complexity of modular design activities. PLM system tools are used for handling a variety of product definitions, to manage workflow of development activities, and to measure relational properties such as cost and performance. Companies often use a PLM tool for management of CAD files, documents, and drawings, but they do not take advantage of the full potential of the PLM system to support the development activities of modular product designs. The key result of this paper is the description of an empirically tested approach using a visual product architecture representation in combination with a PLM system to support the development of a product family of complex products. The results from the study encompass new PLM capabilities for handling multiple product structures, visualising multiple architectural views on products, controlling interfaces, and quantifying and communicating the status and progress of product-related resources.

Keywords: *Product lifecycle management (PLM), architecture based development, product models, modularisation, interface management.*

2. Introduction
In the wake of the financial crisis companies are facing increasing pressure to develop solutions faster and at lower cost. The changed circumstances put great pressure on manufacturing companies, requiring them to increase their R&D efficiency by providing new competitive solutions faster; and at the same time cut costs by improving product quality and productivity in production. Modularisation, appropriately applied, can serve as a means to provide the variety needed from a customer point of view and at the same time reuse sub-solutions across different products to improve time-to-market and maintain predictable product quality [1]. However, the complexity of man-made product systems has in recent years grown to an unprecedented level. Many companies do not succeed in developing modular architectures, as modules are not easy to identify in products where key functionality is distributed across the product structure [2]. In this situation computer-based supporting tools have become a necessity in order to handle complexity in all aspects of the product design. One strategy for handling complex product systems is the introduction of PLM system tools, to obtain comprehensible product representations without neglecting relevant aspect and dependency types [3, 4]. The most prominent idea behind PLM systems, or the top-down perspective on new product development, is that companies can create more value by integrating

data from multiple systems in order to obtain synergies of all available product-related data and to eliminate redundant data existing in different system environments. In that way PLM systems aim to support collaborative work within product design processes in order to integrate partners and all associated knowledge efficiently [5-7]. A secondary view on PLM technology is related to a bottom-up perspective. It considers that knowledge of available tools can allow appropriate solutions to be found for company-specific problems. Both perspectives are considered equally important when approaching PLM [8, 9]. However, many manufacturing companies deploy PLM systems in an ineffective way, merely for documenting and managing product data as CAD files, product related documents, and drawings. The result is that firms might find themselves quite far from the expected operational or strategic outcomes from PLM tools [10-12].

This paper is based on the assumption that the definition of a visual architecture representation and the operational handling of it in a PLM system can enable companies to overcome the challenging situation of identifying modules when developing product families. The paper describes an approach for deploying PLM system tools to support the development of modular products, providing functionalities for defining and evaluating modules and their interfaces in a product family context. The approach is based on a visual architecture description, expressing a product family's structures (how it is built up) seen from different viewpoints. An architecture viewpoint here is defined as a work product establishing the conventions for the construction, interpretation and use, to frame specific system concerns [13]. The architecture description can be used for configuration, i.e. identification of modules and module variations, and basic rules for interaction and interfaces between modules. This again allows grouping of variants according to commonality and application areas.

The visual architecture description, however, has some drawbacks due to the large amount of information that has to be visually represented and updated during development. The challenges by using visual product models for developing modular product designs are linked to the difficulties in handling large amounts of information in a dynamic way. Some of the challenges are, among others:

- Difficult to integrate the development over several departments, totalling thousands of employees.
- Difficult to recognise and manage modules and interfaces because of product data scattered in both CAD systems and other architecture descriptions.
- Difficult for designers to find and re-use existing modules.
- Difficult to carry out monitoring of design progress during a project because of the distributed development.
- Difficult to manage interfaces i.e. designing interfaces and controlling interfaces for change.
- Difficult to see the implications of Engineering Change (EC) of already released structures.

The contribution of this paper is to describe the integration between a visual architecture description and product definitions in a PLM system environment. This is done in order to have the best of both worlds: Utilize visual architecture descriptions to create overview, improve communication and collaboration, and to support the creation of modular product structures; and to utilize a PLM system to manage and integrate product information from the architecture descriptions effectively.

The approach is the result of several action research-based studies, and has recently been applied in another case study with promising results, which is presented here. The empirical base for this study is a large Danish manufacturer of complex products related to the renewable energy sector. The PLM tool applied to the described approach is created by PTC®, and marketed under the name *PTC*

Windchill PDMLink 9.1. The approach has also been implemented in Siemens TeamCenter®, but this case will not be included in this paper.

The paper is structured as follows: First, a brief introduction to the theoretical basis and the concepts relevant to this research. Second, the suggested approach and its methods and models are described. Then the case is described and the results by implementing the approach are presented. A discussion extracts the principals, relationships, and generalisations from the results. Finally, a conclusion sums up the experience of implementing and testing the approach in a case study and the suggestions on future work.

3. Theoretical foundation and related work

The literature relevant to this paper has its basis in the Theory of Technical Systems [14] and Theory of Domains [13]. The theories' primary role is the support of function and property reasoning. A secondary role of the theories is to support concepts for product modelling which again suggests wide application in architecture thinking. In accordance with Theory of Technical Systems, this article will primarily reserve the word *structure* for how individual products are built up and *architecture* will be reserved for describing how a product family is built up including the future derivative products. Literature addresses a variety of concepts related to architecture thinking that in short will be described: product platform, product architecture, modularity, and product family. To expand the research base, the present status of PLM tools in industry has also been considered.

3.1 Product platform

The basic thinking pattern behind the later described architecture framework has strong relations to the concepts of product platforms. Platform thinking, the process of identifying and exploiting commonalities among a firm's offerings, target markets, and the processes for creating and delivering offerings, appears to be a successful strategy for creating variety at low costs. The commercial exploitation of a product platform is perhaps better known as mass customisation. Mass customization is originally a manufacturing strategy aiming at satisfying individual customer requirements while keeping manufacturing cost and delivery times close to those of mass-produced products [15, 16]. A product platform has been defined by Meyer et al. [1] as a set of subsystems and interfaces that form a common structure from which a stream of related products can be efficiently developed and produced. Product platforms are therefore specifically designed to serve one specific group of related products. A product architecture is not essentially developed with this limitation in mind. Baldwin and Clark [17], page 77, define three aspects of the underlying logic of a product platform: (1) its modular architecture; (2) the interfaces (the scheme by which the modules interact and communicate); and (3) the design rules (that the modules conform to). The three aspects will be explained next, because they are important to the approach presented in this article of PLM support of modular product development.

3.2 Modular architecture

An important principle of architectures is the concept of modularity, i.e. the concept of decomposing a system into independent parts or modules that can be treated as logical units. This enables concurrent development of modules and forms the basis for configuration of product families [18, 19]. Modularity has been defined as the relationship between a product's functional and physical structures such that: there is a one-to-one or many-to-one correspondence between the functional and physical structures— and unintended interactions between modules are minimised [18]. Although exact definitions vary on modular architectures, the fundamental ideas are common throughout: Break systems into discrete modules; ensure modules can interchange with each other;

and provide well-defined interfaces. Modular architectures thus fully specify component interfaces and therefore limit successive component development. The approaches for designing modular architectures are multiple. Some focus on the technical aspects of architectures [17, 18, 20, 21], while the economic aspects are dealt with by others [1, 2, 22, 23]. A modular design strategy both enables, but also demands, parallelism in design activities and collaboration between a diversity of disciplines in companies. This again involves supporting methods and tools for enhancing interaction, design management and communication. Architecture descriptions are used by the parties that create, utilize and manage product systems to improve communication and co-operation, enabling them to work in an integrated, coherent fashion. Architecture frameworks and architecture description languages are being created as assets that codify the conventions and common practices of architecting and the description of architectures within different communities and domains of application [24]. The product architecture defines the basic physical building blocks of the product in terms of what they do and what their interfaces with the surroundings and the rest of the device are [20].

3.3 Interfaces

In this paper, we address the part domain and use the term "interface" synonymously with part interface, being the connection between subsystems or components of a product. The subsequently explained *System structure* is based upon a functional product view where elements are grouped by their functional identity i.e. a system delivers one or more active effects. Several authors have classified interfaces in the part domain. Pimmler and Eppinger [25] proposed a taxonomy of interactions between components, namely spatial, energy, information, and material types. Interface management in the part domain deals with the issue of interface design and interface control [26, 27]. Interface design is about the creation, form, arrangement, and configuration of interfaces, whereas interface control focuses on ensuring compatibility of interfaces during the design phase. Ensuring interface compatibility is the process of identifying all functional and physical characteristics of interacting entities from different organisations, and ensuring that proposed changes to these characteristics are assessed and approved before implementation. Interface management is an important aspect of the suggested approach of using PLM capabilities in product family development.

3.4 Design rules that modules conform to

Configuration is mainly the task of choosing between various variants for subsystems, while respecting certain design rules and constraints [28]. The encapsulation in modules is governed by the desired effects, and the clustering will depend on the drivers for a platform approach, i.e. whether product customisation, upgrading, or outsourcing etc. is the main reason for the grouping to take place [23]. Consequently, the module design has a strong relation to the strategic reasons behind the layout of an architecture and which products have to be derived from it. Modularisation is the task of deciding which characteristics to group and which characteristics to separate [17, 29 - 31]. Deciding on the common and variable proportions of a product family has strong ties with the product design and production capabilities, because they largely determine which attributes are easy to decouple, which again has an impact on the module creation [16, 32, 33]. The PLM system used in this approach has capabilities to monitor the impact of creating specific modules and thereby offers a proactive exploration of the optimal modular architecture for a product family.

3.5 Enterprise PDM/PLM systems

The functionalities of enterprise PDM tools have evolved in the last decades and today PDM is in many cases seen as a subset of modern PLM system tools [9]. Product Data Management (PDM) technology is intensively used in industry and today its application is mainly focused on particular product lifecycle phases, e.g., development, prototyping or production [5, 9, 34]. In recent years, PDM vendors and integrators have found a multitude of acronyms, e.g., PDMLink, TeamCenter PDM, Collaborative Product Development (cPDM), 3D Product Lifecycle Management (3D-PLM), and Virtual Product Development (VPDM). In reality, acronyms and descriptions are converging to Product Lifecycle Management (PLM). PLM is the extension of PDM towards a comprehensive approach for product-related information and its management within an enterprise. PLM refers to the management of the product definitions, e.g. product data within product development, but in the essence of the definition, product data of the whole lifecycle of the product. This includes planning and controlling of processes that are required for managing data, documents and enterprise resources throughout the entire product lifecycle [34]. The environment of PLM systems can be characterised by the co-existence of various independent tools, each based on its own specific product model [35]. This has been acknowledged by others and proposals of frameworks for supporting the full range of PLM information needing to form a common product definition have been described e.g. by Sudarsan [36].

3.6 Conclusion

The related work points out major methodological concepts related to the discipline of developing product families. However, there seems to be a gap in developing product families supported by PLM systems tools. Companies often use PLM systems for management of CAD files, documents, and drawings, and to access various independent computer systems holding their own product definitions. The coexistence of these independent tools with their own specific models of the product or product family brings redundancy in the digital product documentation. The strength of a PLM system derives from its shared product definition in which dependencies and relations can be both monitored and manipulated from a central entry point. The risk of having a support system without access to the content of product models is that important dependencies are overseen in the development process. There is therefore a need for making prescriptive studies of using PLM systems for supporting a common product definition in order to create the optimal balancing of a modular architecture.

4. Research methodology

The approach presented in this article is the result of several action research-based studies conducted with manufacturing companies. These studies have matured the approach to its current state and subsequently it has been tested in a case study with promising results. Engaging in the practical setting of the case study, different types of inquiries were in practice. During the analysis phase of the study, the inquiries were rather exploratory and diagnostically based, helping the researchers to understand the situation and assess the applicability of the approach. Moving on to the synthesis phase, the inquiries changed to having more of a confronting character and being directly prescriptive.

As one of the aims of the research is to bridge information from different engineering domains, there was a need to create a boundary object enabling the different competences to interact, exchange ideas, and understand each other's work challenges [37]. Thus visualization has been used to create such a boundary object to facilitate collective alignment among engineering professionals. From the early stages of the project the concept architecture has been illustrated on a large A0 poster, allowing professionals with different backgrounds to gather around a large poster and make review meetings efficient by taking advantage of the optical consistency such a visualization represents. The working method enables participants to lay aside their daily working habits and see the challenges in the project as the 'same type'.

5. Approach for using PLM to support modular development

As stated in the introduction, the approach is grounded in an architecture modelling framework developed at DTU [38]. The relation between the architecture framework and the PLM support approach is highlighted in figure 1 (*Scope of the approach*). The basic idea of the authors' architecture framework is to enable the alignment between a company's products and their production, marketing, sales, distribution and the company's involvement in delivering service and actively participating in re-use, recovery and disposal. The assumptions behind the framework will in short be explained in the following.

The framework covers four perspectives on a product system: The market, the product family (how it is built), the production, and the roadmap for deployment. The purpose of modelling the market architecture is to bring precision into decision making concerning the choice of which segments to cover or not cover and what properties are needed in order to do so across different business areas with different applications. A clearly defined market architecture is able to guide and control the engineering efforts towards profitability by scoping product family design. The modelling of product architectures covers the basic structural elements of a product family and the behavioural functional abilities. In other words, the aim of these modelling techniques is not solely to describe what the product architecture is, but also what the product architecture is able to do. Depending on the size of the product architecture development project, the associated production system will need an update, a modification or a complete redesign. The production system is designed coherently, as the product architecture matures and passes from concept to detailed design. Finally, the behavioural aspects of the market-, product- and production architecture are considered in the "architectures'" future launch preparedness. This is a function of the architecture, explaining what the architecture is able to do. This ability is modelled by visualising the launches, derivative products and specific product updates.

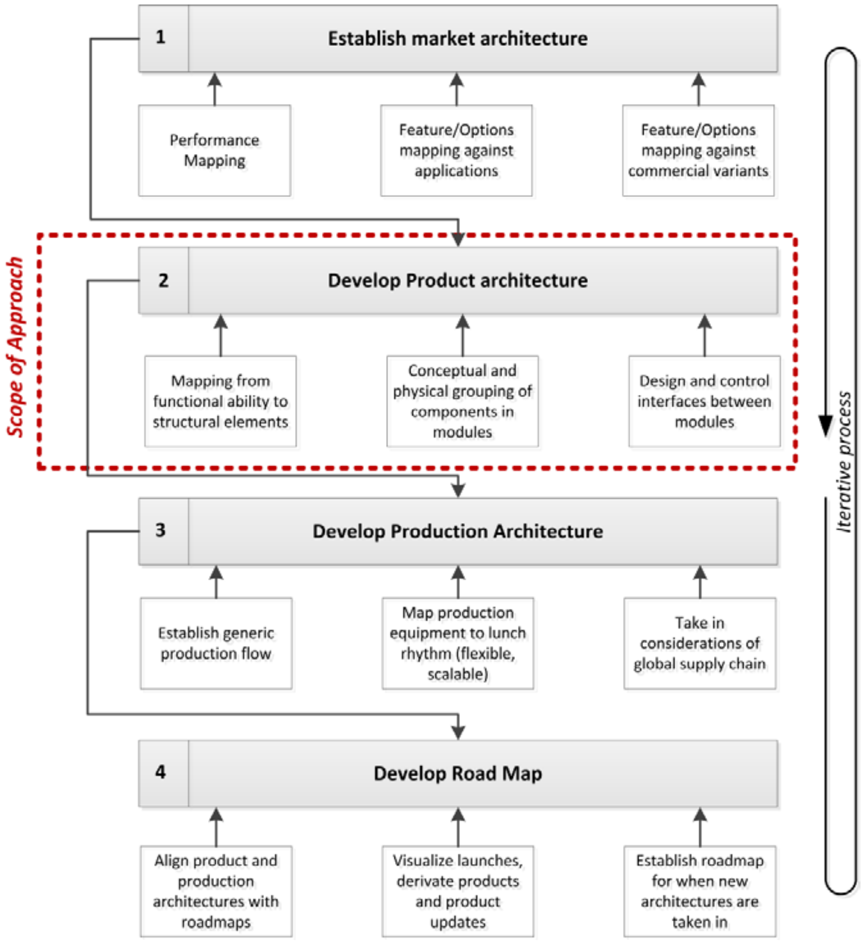

Figure 1. Framework for Architecture-based product family development, based on work by [38]

The approach is striving to support the development of the product architecture i.e. the mapping from functional ability to structural elements, the conceptual and physical grouping of components in modules, and the design and control of interfaces between modules. The steps of the approach of using PLM systems for supporting development of modular designs is outlined in figure 2. Each step will be covered in the subsequent sections.

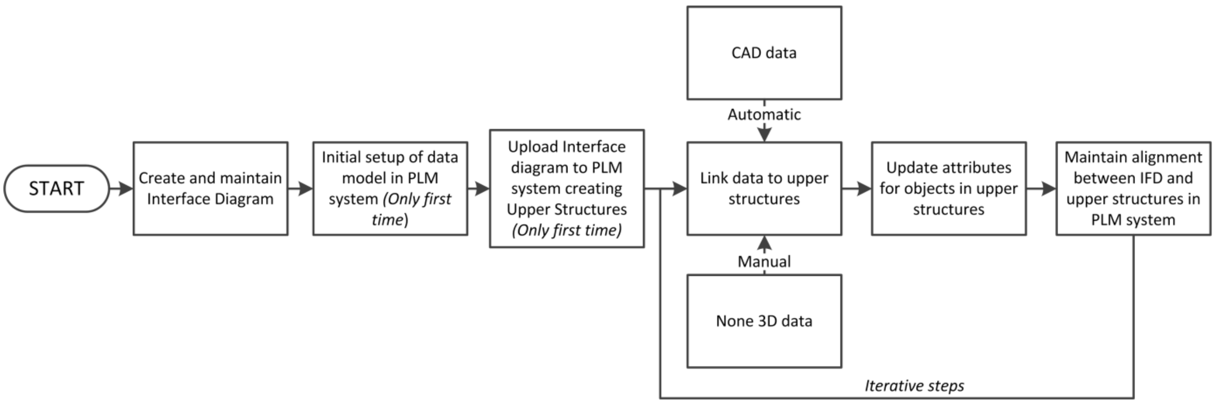

Figure 2. Steps in the Described PLM approach

5.1 Create and maintain Interface diagram

As outlined in figure 2, the approach begins by establishing a visual product architecture representation named *Interface diagram.* An Interface diagram is an architecture representation capturing structural characteristics of a product family, combining the aspect of mapping between functional ability and structural elements domains. The model puts emphasis on managing interfaces between components in the model, hence the chosen name of the modelling tool. The formalism is denoted *Interface diagram* which has its basis in the *Generic organ diagram* presented in the work of Harlou [39].

The formalism is illustrated and described by using an example of an Interface diagram conducted for a product family of *Bobcats.* The model puts emphasis on handling the product family seen from different viewpoints. The main viewpoint is a system perspective i.e. the perspective that deals with the product's main functions or a related lifecycle. Figure 3 shows the structure of two of the systems in the Bobcat: the hydraulic system and drive train system. The two systems are physically allocated to different sections of the Bobcat and are connected by interfaces such as hydraulic hoses, electrical wires, transmission belts etc.

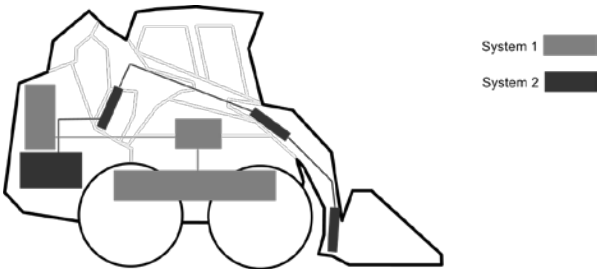

Figure 3. System structure of a bobcat showing entities belonGING to systems and the relations between them

As seen above, the components included in the system can be spread throughout the complete vehicle. The purpose of focusing on system development is to support functionality in components that are spread across multiple modules. Systems are often characterised by one or more of the following:

- Deliver important functionality, e.g. steering, braking, loading etc.
- Is a complex or new technology, e.g. hydraulics, cooling etc.
- Organisation – alignment with organisational structure and/or affecting organisational structure.

The objective of the system design is to focus the design on functionality and performance. An example of a system in the Bobcat could be the hydraulic system. It consists of a hydraulic pump, driven by the combustion engine, and actuators to manoeuvre the lifting arm and shovel; valves, filters, pipes, hoses, oil reservoir etc. All parts have to be taken into account when designing and dimensioning the system to meet the required performance properties. The same component can, from a functional perspective, be a part of multiple systems e.g. the combustion engine which is both a part of the hydraulic system and the drive system.

Because of initiatives for modularisation (carry over, serviceability of modules, outsourcing of design and production etc.) it is appropriate to manufacture the Bobcat in modules. The second viewpoint handled in the Interface diagram is a modular viewpoint in which systems are split and physically joined components are encapsulated into modules. Modules can consist of elements belonging to different systems, i.e. developed by different system teams. It is therefore crucial both to integrate systems in modules and to handle interfaces created along the module boundaries splitting systems. Figure 4 shows the conceptual architecture in which the two systems are split into three modules— Base frame module, Engine module, and Hydraulic module.

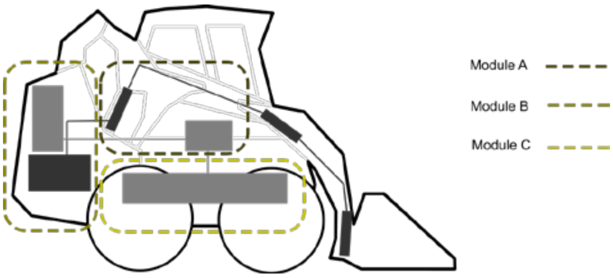

Figure 4. Module structure in a bobcat showing entities belonging to modules and relations between systems and modules

As an example, the Hydraulic module is a physical sub-assembly consisting of the hydraulic pump, the oil reservoir, hosing, and structural components such as a frame, clamps, and screws.

The modelling formalism of the Interface diagram has been described in previous work [40], but will in short be explained here. The Interface diagram is modelled by means of blocks and lines in a diagram software tool, MS Visio. The tool is suited for object oriented modelling and structuring different perspectives of architectures in layers. The Interface diagram is normally printed on large A0 blueprints in order to get the overview of the architecture it represents, and is used as a boundary object between different developers (see section *Research methodology*). Figure 5 is a symbolic representation of an Interface diagram. In order for the reader to quickly understand the structure of the product, it is suitable to model the diagram so the layout is established as a cross-section of the actual product. In that way, the physical layout of the product can be recognised in the diagram. The diagram is read by following the interfaces. For products that process or transform objects, this gives a logical reading direction; for other products it is up to the reader to find a suitable flow in the model. The main elements of the diagram formalism are functional objects denoted Key components. The purpose of the Key components is to decompose the systems and modules into smaller building blocks. Key components can have different characteristics and are thus modelled in different ways. Each Key component belongs to one or more product system. To avoid confusion, systems and their interaction must be clearly defined. This is done by choosing the relevant interaction as a basis for determining the system boundary. There is no fixed list of systems to be included in the development. Systems can be modelled and thereby control important properties of the final product. Modules are modelled by arranging Key components inside boxes with a thick black boundary and rounded corners. All modules are assemblies of physically joined components forming one bill of material (with possible multiple levels). Modules can contain smaller modules, but they do not overlap as it is clearly defined to which module any element in a product belongs.

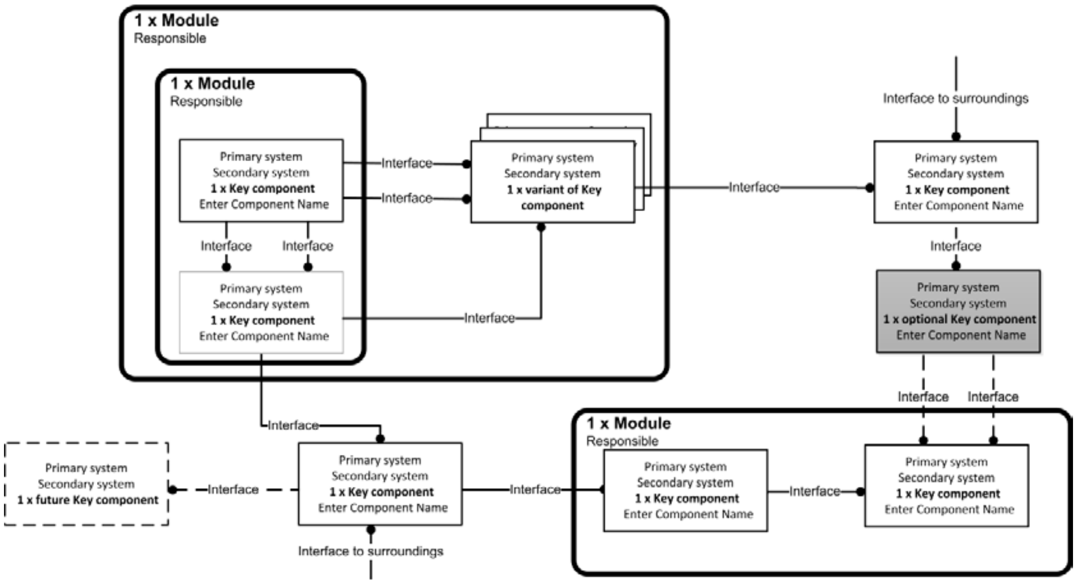

Figure 5. Symbolic representation of a generic interface diagram [41]

The structure of the Interface diagram appears as the relations, i.e. interfaces are added to the diagram. The interfaces between Key components are drawn with lines that represent a relation. An interface among two Key components represents a physical relation, e.g. physical connection, energy transportation, information flow or flow of material. The purpose of working with interfaces is to ensure responsibility for the components' interaction and to ensure that components are interchangeable, when relevant. An interface between two Key components holds a definition on which one is the master and which one is the slave of the interface. This enables responsibility for a Key component to monitor whether he or she owns the right to change or modify the related interface. There exist a number of interface classes and the list can be extended to support the context of a product. Examples of interface classes are: mechanical, spatial, cooling air, cooling liquid, electrical measurement, electrical signal, electric grid etc. The dot at the end of the line indicates the responsibility of the interface. Optional interfaces can be modelled on the diagram to show affected relations between entities or systems if the interface is established.

5.2 Setup platform in PLM system

In collaboration with the vendor, the PLM system has been prepared to handle multiple structure views. The primary task was to set up the data model. The object types and their relations are illustrated in Figure 6. A dotted line in the figure illustrates the split between *Upper structures* defined in the Interface diagram, and *Lower structures*— that is all other data linked to objects in the Upper structures. The difference will be explained in the section of linking data to Upper structures. The objects have been implemented as soft types of the type *WTPart*. For the interfaces, each classification of the interface has been implemented separately. Furthermore, a number of attributes were added to each object to contain non-structural data i.e. ownership, optionality, variance etc. A new product folder and sub folders for each object type were created to hold all objects and ease managing access rights.

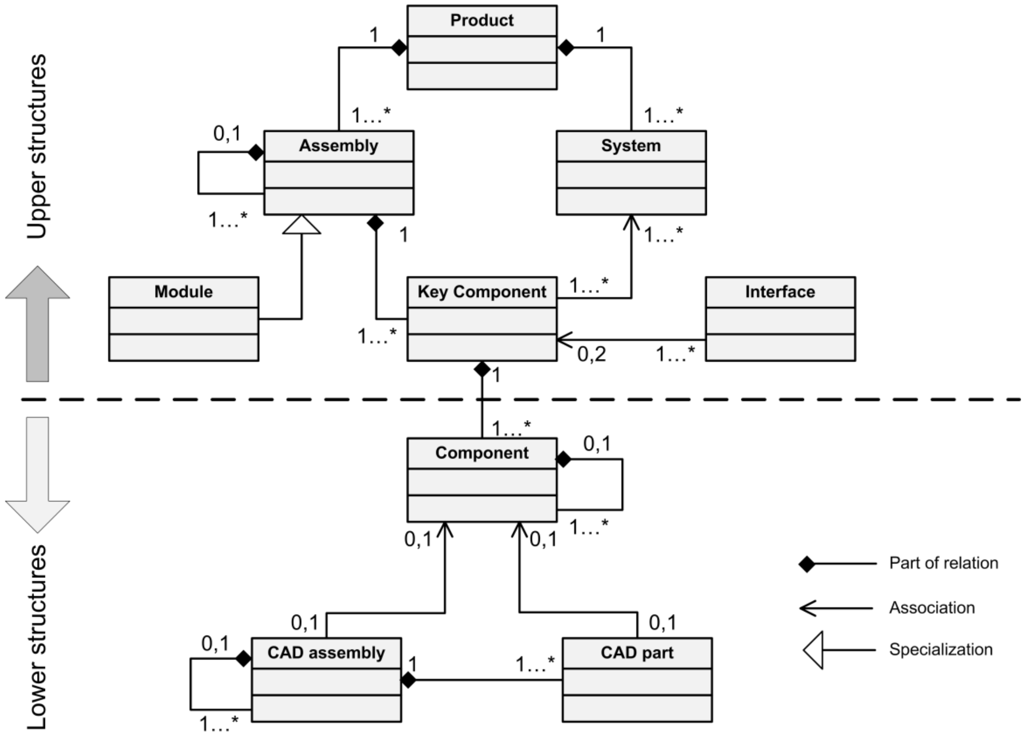

Figure 6. Entity relationship model of data structure in PLM system (UML)

The objects have been carefully defined to provide the functionality of multiple structure views, yet able to handle the interdependencies as: systems split by modules, modules containing elements belonging to different systems, interfaces between different system elements etc. The PLM objects are listed and described below.

Product: The product level deals with the complete product family, e.g. the whole product system. A product consists of assemblies and systems.

System: The system elements are grouped and labelled by their functional identity, related lifecycle or could be aligned with an organisational structure, and applied for articulating a structure of systems. A system is seen as a means of a product, which realises its function and carries its properties. The relations between system elements are constituted by part interfaces which deliver active effects (input/output) based upon physical, chemical or biological phenomena. System elements can be differentiated substructures localised spatially in the larger product structure. The purpose of system development is to support functionality in components that are spread across multiple modules.

Assembly: A product can be decomposed into physical assemblies. An assembly contains physically joined Key components forming one bill of material (with possible multiple levels). An assembly can consist of other assemblies, modules and Key components. In contrast for systems, assemblies cannot overlap, meaning that any given Key component, assembly or module can only be a child of one other object. It is worth noticing that components cannot be assigned to assemblies. Likewise, systems cannot be associated with assemblies.

Module: A module is a special type of assembly, following the same rules as just described. The difference between an assembly and a module is the purpose of a module regarding changeability, serviceability and reuse. The module must have well-defined interfaces i.e. assembly relations. The system structure sets the requirements for the module structure, but the module structure and the module functionalities are also determined by materialisation and assembly arrangement.

Key component: Key components are the smallest entities known from the Interface diagram. The purpose of the Key components is to decompose the systems and modules into smaller building blocks. The Key component is the constitutional element of assemblies and modules. It consists of components, CAD-assemblies and CAD-parts. Interfaces are assigned to Key components, and Key components only. Each Key component is assigned one primary system and optionally one or more secondary systems.

Interface: An interface among two Key components represents a physical relation, e.g. physical connection, energy transportation, information flow or flow of material. The purpose of working with interfaces is to ensure responsibility for the components' interaction. Also to ensure that components are interchangeable, when relevant. An interface connects to two Key components. One of the Key components is the master and the other is the slave. The master Key component has the ownership of the interface, i.e. specification, design, documentation, cost, etc. Interfaces can be of different kinds (e.g. cooling, internal power, etc.) and Key components can have multiple interfaces attached to it.

CAD assembly: The CAD-assembly is the assemblies defined in a CAD-system. The CAD-assembly is the constitutional element of Key components and components. It can consist of CAD-assemblies, CAD-parts or components (with no CAD data).

CAD part: The CAD parts are the parts defined in a CAD-system. CAD-parts can belong to a CAD-assembly. The CAD-parts are the constitutional elements of CAD-assemblies and components.

Component: Components are the smallest elements considered in the development process. The objective of the component level is to develop components that suit the requirements of the systems and modules that they support or are part of. Components can consist of other components, CAD assemblies and CAD parts. Components are the constitutional elements of the Key components.

Four structures are needed to accommodate the product structures of a product family. The four structures are implemented as view variants of the same top-level object. The structure views are described below.

- **Design structure:** This view contains the complete CAD assembly structure. This structure is driven from the CAD application and is not altered when building up the other structure views. The CAD objects from the Design structure are linked to the Components.
- **Module structure**: This view contains all Modules, Assemblies, Key Components and Components. This structure is showing a 100% BOM, meaning every component is shown exactly once.
- **System structure:** This view contains all Systems, Key Components and Components. This structure is overloaded, because as Key components can be associated with multiple systems, they will exist multiple times in the structure. If a filter is applied and only primary system relations are shown, it will not be an overloaded BOM.
- **Interface structure:** This view contains all interface classes, Interfaces, Key Components and Components. The structure is overloaded, as one Key component can have multiple interfaces and therefore will show up multiple times in the structure. In the relation between the interface

and the two Key components, an attribute shows which one is the master and slave, respectively.

The Design structure is made manually by adding the top CAD assembly to the design view of the product node. The other three structures are created automatically, based on input from the Interface diagram, as described in the following chapter.

5.3 Upload Interface diagram to PLM system

The process of getting all the information from the Interface diagram and into the PLM system is basically divided into two steps: exporting from Interface diagram and importing into PLM. An interchange format based on XML was defined to contain all information from the Interface diagram and was used to contain the data between export and import (see Figure 7).

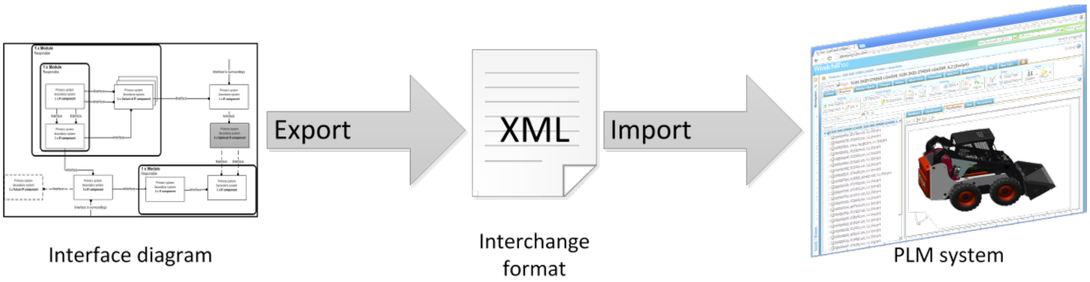

Figure 7. Illustration of Data transfer from Interface Diagram to PLM system

5.3.1 Interchange format

The interchange format was designed to contain all information available in the Interface diagram and is a solid way to reach the attributes and structures from other applications, including a PLM system. The format is not limited to getting Interface diagram data into PLM, but is currently also used for various reporting, structure-compare tools, structure-modelling tools etc. The format reflects the module structure and is hence hierarchical, human readable and contains no redundant data. This is possible as the module structure is a 100% structure where all objects exist exactly once — opposite to the system structure. If the lower structure (CAD data) was to be included, the hierarchical data structure would likewise contain redundant data, as the same assemblies are used in multiple Key Components. The hierarchical format enables quick visualisation and meaningful reading/editing in a simple text editor. The format is illustrated in figure 8.

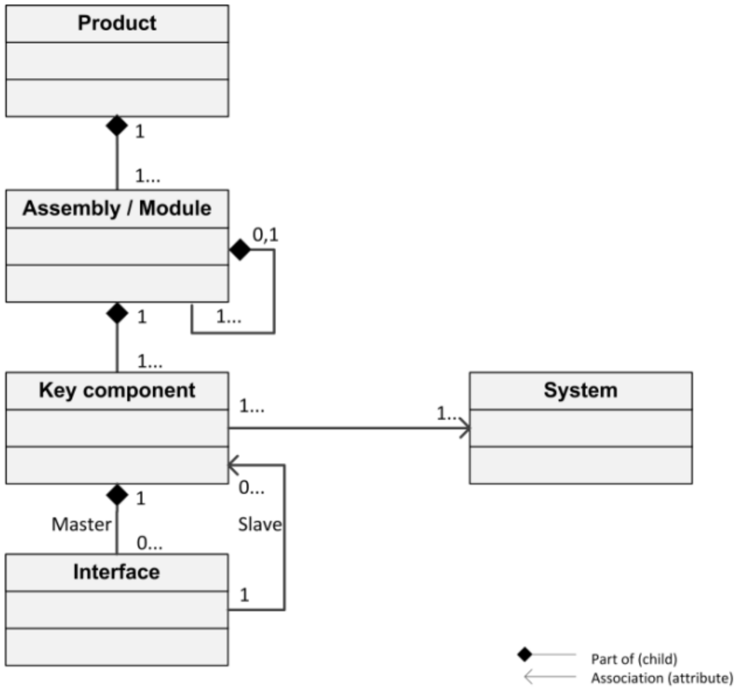

Figure 8. Hierarchical format of structure

The top element is of the type *Product*, and holds the complete product structure. Apart from empty elements containing different attributes, it contains *Assembly* and *Module* elements. These can contain *Assembly*, *Module* and finally *Key Component* elements. *Key Component* elements have an empty element for holding system relations as a comma-separated string — the first being the primary system. *Key Component* elements contain the *Interface* elements for which they are the master. The *Interface* elements have an empty element for holding the ID of the slave *Key Component*. For all elements it is true that business attributes, like name and responsibility, are implemented as empty XML elements and technical attributes, like ID and source application, are implemented as XML attributes.

5.3.2 Export Interface diagram to interchange format (XML)

Visio has native support for Visual Basic for Applications (VBA), which is a scripting language supporting the Visio object model, meaning it has built-in functions for working directly on the objects defined in the Interface diagram. The export function was implemented as a macro in VBA in an independent Microsoft Visio document. The macro starts by locating the Visio application instance and the Interface diagram document and sheet. If successful, it loops through all objects and stores them in an array. If some objects already exist in the PLM system, a file with IDs can be loaded and objects are populated with the IDs. Also, Excel sheets containing BOMs of Key Components can be loaded and added to the structure. The parent/child relationship between objects is defined visually: an object surrounding another object is the parent of that object. This relationship is not explicit to Visio, thus logic is needed to identify the relationship. This is done based on the position and size of each object and is populated by the array holding all the objects. The order of objects sharing the same parent is likewise not explicit to Visio. Some PLM systems order objects alphabetically, in which case the order is trivial; but for systems supporting a custom order, the order is kept as close to the Interface diagram as possible. Interface diagrams are often structured with a goal to match the physical product as much as possible to support people in getting overview and locating objects, and that overview we want to maintain in a later visualisation of the structure in e.g. a PLM system. This is achieved by ordering objects based on their position, the first being the uppermost left object, implemented as the sum of the x and y components in ascending order.

5.3.3 Import interchange format (XML) to PLM system

The utilised PLM system offers multiple methods for automation. The chosen technology is named Windchill® Info*Engine®, which is a scripting language that works directly on the implemented data model. Consultants from PTC® supported this activity.

The script runs in three steps: 1) transform interchange format, 2) create new objects and 3) create new links. Firstly, the script traverses the XML document and transforms it into two new data load files; a file containing all the objects that need to be created, including all the object attributes, and a file containing all the links that need to be created, including quantity. These files are in a standard PTC® XML format. Secondly, the script loads the newly created object file and creates all the objects; Modules, Assemblies, Key Components and Interfaces. It also populates the objects with attributes, such as name, responsibility, whether it is optional or has variants. The process takes a couple of minutes for Interface diagrams with 400 Key Components. Thirdly, the script loads the link file and creates all the relations between objects. A part of this process is to locate the newly-created objects and match them with the IDs from the Interface diagram. The process takes a couple of minutes for Interface diagrams with 400 Key Components.

When the script is done, you need to manually link objects to the top-level object. All system objects need to be linked to the system view variant of the top-level object. All top-level module and assembly objects need to be linked to the module view variant of the top-level object. All interface class objects need to be linked to the interface view variant of the top-level object. When this is done, all the structures are complete. This manual process is quite fast but could probably be automated in the future. The script was developed to only enable a one-time load from the Interface diagram into the PLM system, but later experience shows that quite long into the design process, managing the upper product structures is done most efficiently on the Interface diagram, thus a method for continuous alignment of the structures in the PLM system is needed.

5.4 Link data to upper structures

Instead of being an environment with focus mainly on the administration of files generated from specific tools like CAD, the PLM system now contains a master product model. The system contains the comprehensive representation of the architecture for the product family by means of the modelled product structures from the Interface diagram (System, Module, and Interface). The structures in the PLM system are named *Upper structures*, to underline that they constitute the master product model. The structures, representing different perspectives of the product family, can be handled individually in the PLM system without the need for redundant data. The object class Key component is present in all three structures, and the objects can be associated with both geometric data (CAD models) and non-geometric product data characteristics and properties (described in documents and by attributes). People responsible for designing systems and modules are allowed to enrich, create, manipulate, and/or delete data belonging to their specific designs, and every member on the project is able to view information from all elements of the product model.

5.5 Update and maintain Interface diagram and data in PLM system

As the Interface diagram is the master model of the product family and changes are incorporated directly onto a blueprint of it at team-meetings, changes have to be incorporated into the PLM system in order for data structures to reflect the present status. We created a simple software tool that compares the product structures from the Interface diagram model with the respective ones in the PLM system. The tool reports any differences between the structures, and thereby enables manual update of the product structures in the PLM system i.e. creating, deleting, or moving objects. Possible documentation already linked to objects that have to be deleted, has to be handled individually; with the purpose of determining if it can be deleted or has to be reassigned to another object.

6. Case

6.1 Situation

The approach was developed and applied in a large manufacturing company serving the global energy industry with energy generation products. The case company is anonymised for competitive reasons and in order to be able to report more interesting details than a public case allows for.

In the wake of the global financial crisis the customers of the company have experienced financial problems with financing their energy solutions. This has led to price competition in the market, while the company and competitors fight for the limited orders. The external pressure on delivery time has increased, which again has put internal pressure on bringing down development time. In order to accommodate these challenges, the company has focused on a strategy of modular product family development instead of single product development. The modular design strategy demands parallelism in design activities and collaboration between a diversity of disciplines in companies, which again involves supporting computer-based tools for enhancing interaction, design management and communication. The deployment of a PLM tool has been seen as an important facilitator for achieving success with the modular design strategy.

6.2 Description of the approach in use

The purpose of the initial interaction with the company was to support its initiative in architecture-based product development and to support the implementation of the PLM system *PTC Windchill PDMLink.* The outcome of the research was prescriptive in nature i.e. descriptions of the intended support; what it is and how it works.

6.2.1 Visual architecture representation

The first step of the approach was to model an Interface diagram of the new product family. The Interface diagram is a dynamic tool which is updated and refined during the beginning-of-life phases for a product family i.e. concept, design, and realisation. The technique for modelling the Interface diagram was based on interviewing the persons with the insight to model systems in their totality. No single person in the company had the required insight to draw the diagram. Therefore several domain experts had to be involved in giving input to the diagram. Experience from the case company showed that it took a number of months to create a diagram with the required detail to represent the product family. Certain scepticism was expressed among large parts of the development organization. The scepticism was related to the expected extra workload to update a visual representation of the product architecture. However, the opinion turned when the tool quickly enabled designers, module owners and other stakeholders to get an overview of the design status and to evaluate consequences for redesign and upgrade activities. The designers could identify affected parts and modules and who to contact by looking at the Interface diagram. The sequence in the creation of the Interface diagram was to begin with a functional modelling technique (System structure in the diagram) and then to create a superimposed modular structure (Module structure in the diagram). Both structures were afterwards developed and maintained in parallel. The diagram provided all project members with a holistic overview of the product system's present status, which enhanced the parallelism among system development activities. The interface diagram enabled a proactive approach for developing and evaluating alternative modular architectural concepts. This could be achieved because modules could be evaluated when the freedom to design was high and the product structures were still to be fixed.

6.2.2 PLM capabilities

The next step of preparing the PLM system to support the upload of the structures from the Interface diagram was carried out in collaboration with the software vendor. No customization of the PLM system was needed to handle import of the interchange format or represent multiple structures. Export of the modelled structures in the Interface diagram was created outside the PLM environment. Because the PLM system was a completely standard system, there was no extra work for the vendor in supporting use in the implementation phase.

When the Upper structures from the Interface diagram were imported to the system, the actual linking of data was put into operation. As stated earlier, the main purpose of the Interface diagram is to support the design by controlling interfaces. The interfaces were visually documented within the Interface diagram and further described in detail in the PLM system's interface structure. The approach of using the Interface diagram focuses on ensuring compatibility of interfaces during the design phase. Interface descriptions are comparable to *Interface Control Documents* (ICD's) [27]. When a system had complex development and modification processes, agreements between different working teams on interfaces could not easily be achieved. Therefore, interface descriptions were developed by the teams that establish the requirements to which the interfaces should be designed and developed. These descriptions are not proposed to show the detailed data that would normally appear on design drawings. Instead, they show parameters, characteristics, or configurations that are necessary to ensure that the produced system will operate as desired. The purpose of using interface descriptions is to formalise the description of the connectivity between two systems. The typical information that is described in an interface description is document purpose, the description of the interface, relevant block diagrams, interface functions, their performance, their configuration, and essential features.

In the company, the PLM system was now representing a consistent product model containing multiple structural descriptions, and the previous master role of the CAD-system in the development project changed significantly. The CAD-system now acted as a sub-system of the PLM system, which administrated geometrical descriptions of the products. It offered direct access to parts of the geometry by means of standardised procedures that could be addressed and utilised by the PLM system. The different structures of the product model point to the geometry (assemblies or parts) while CAD-data is linked to objects in the Upper structures (Key components). In that way CAD-models could be monitored differently, without having redundant models in the CAD-system. This is illustrated in figure 9. Different products of the family could be configured by the PLM system, or at single product level representing a system, module, or interface structure. That made it possible for teams responsible for different designs in different life cycle phases to have simultaneous access to the current state of the CAD design— and therefore be able to identify conflicts in the design of systems and modules.

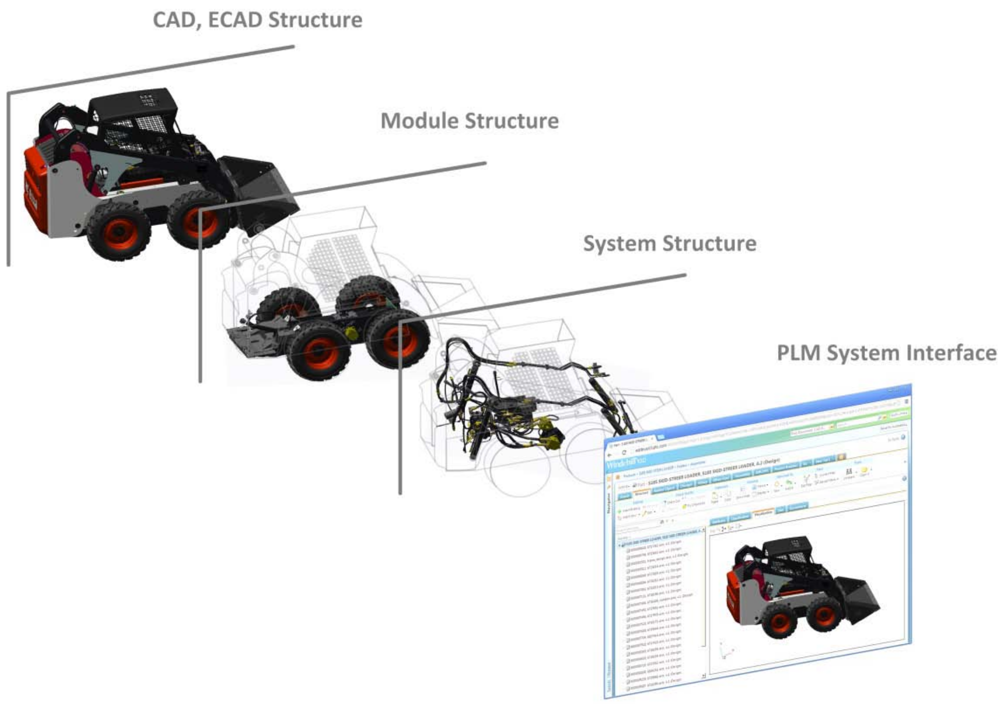

Figure 9. Visual capabilities for seeing interactions between system and modular structures

The PLM system provided continuous computer support because there was no fundamental difference between ‘early’ and ‘late’ phases. The integration of non-geometric characteristics and properties in the system allows for a representation of requirements from the beginning; that is, at a time when perhaps no characteristics are known at all. The three main structures with their characteristics are:

- System structure: Systems (e.g. cooling or hydraulic) are defined in a structure representing the bill of material seen from a system point of view, which can, for example, enable 3D visualisation of the systems and automated reporting of the cost and weight of each system.
- Module structure: Modules are defined in a structure representing the bill of material seen from a module point of view, which enables 3D visualisation and automated reporting of factors such as the cost and weight of each module.
- Interface structure: Interfaces are clearly defined in a structure representing different interface types, and it is unambiguously defined which components and modules are related to each interface, and which system holds the responsibility.

For the company, the approach expanded the capabilities of PLM beyond the handling of mainly structural data and information i.e. characteristics and dependencies between them. It was able to support the control and management of the design process itself. The product model in the PLM system evolved during the project, and the processes were managed by means of already built-in work flow management capabilities. A part of the approach was to develop reporting capabilities (see figure 10). Reporting functionality was established in the PLM system and was used to monitor design progress on a weekly basis. The numbers of new, modified, and approved parts were used as indicators of the progress of the design. This resolution level enabled early detection of design conflicts e.g. the risk of not being on time with designs. Furthermore, a report on the product cost was generated weekly.

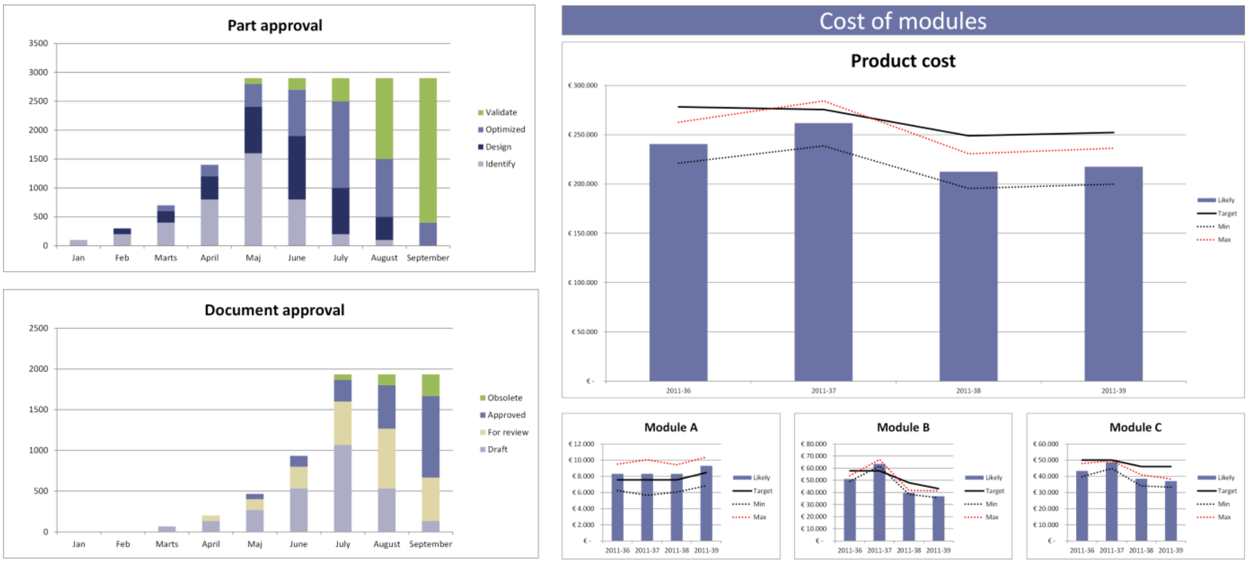

Figure 10. Examples of Reporting showing Design progresS and cost development on a weekly basis

Every component in the system was allocated an initial target cost attribute, and gradually direct cost was added to all components as they were developed or purchased. By means of simple roll-up mechanisms, cost was added from the top product level and down to the smallest components. If a cost element was missing on a component, a target cost stepped in. Target cost numbers were provided by financial controllers in collaboration with the relevant developers and purchasers. Cost reporting became in that way a strong tool for supporting a design according to budget because derivations between budget and actual cost were discovered quickly.

7. Results

The R&D resources saved and the reduction of lead time have not been quantified in a structured way due to two factors. One, the project has not been completed yet. Two, it was difficult to compare this project with others because the project also included development of radical new technologies. The team responsible for maintaining the Interface diagram in the company made the quantitative estimation of a 25% reduction of lead time in early development. This reduction was mainly achieved because of an improvement in concurrency of development activities.

However, the implementation of the approach of using a visual architecture description in combination with a PLM system showed some promising qualitative results. By interviewing the members of the management team and the 14 different design teams, the following statements could be reported as results of the implemented approach:

Management

- Design readiness much clearer earlier in the projects.
- More transparent cost deviations.
- Design progress more accurate to measure on a weekly basis.

Designers

- Very little extra work when thinking in architectures for a family compared to single product development.
- All engineering teams have access to the same single source of information.
- Easier to develop and evaluate module concepts in the early design phases.
- More effective reviews.

Today, the company is working with their PLM system as a central tool to support development activities. Also the organisational anchoring of the architecture thinking patterns, methods etc. utilised in this project is also a derived activity as are the implications for portfolio management, road mapping, product and production technology etc.

8. Discussion and reflection

This section discusses the effects of using the computer-based approach and for which types of projects it appears to be advantageous. For the company investigated, the implications of having one master product model instead of having product definitions spread in multiple IT tools are furthermore addressed. The described approach should be seen as contributing to the research area of architecture- based development i.e. the development of product families. The approach is constituted by methods and tools for creating support in product development and in particular in the area of product definitions.

8.1 Case

This illustrated one case does not justify wide generalisations or provide general proof of the suggested benefits. In this research setting, the findings, however, support the formulated hypothesis of creating support when developing modular designs. Even if strict definitions differ, the fundamental principles of modular design are common: break systems into modules, ensure modules can interchange with each other, and provide well-defined interfaces. Results from the case study show that using a visual product architecture model in combination with a PLM system provides the support for developing on a high conceptual level, but still being able to manage information on a very detailed level.

A strength of this approach is that it can be used in companies developing products for a variety of customers and industries. The approach establishes a common product definition of the product family, creating a better basis for developing modules. Making modular designs by decomposing and separating technologies into functional groupings also simplifies the process of the design. If designers had to work with many thousands of parts they would drown in a swamp of details. By decomposing a product into building blocks (modules), designers can focus on them separately, and more easily see how these fit together to contribute to the working of the whole.

A weakness to the approach is that it is somewhat resource demanding to implement. Even though design engineers reported that very little extra work was used in the architecture-based development, it is not without effort to decompose a product into functional building blocks. It costs something — mental effort at the very least. So it only pays to divide a product into modules if they are used repeatedly in a number of products, or if they comply with another argument for module creation. Another cost is the implementation of a PLM system, training in using the tool, and in learning the methods constituting the approach of using it. For the case study this has required resources from the company, the software vendor, and external PLM consultants to implement, maintain, and perform training. An actual quantification of the resource demand has not been performed as the project is yet to be completed.

A general observation is offered on the implementation of the approach in the company: In the beginning of the project the approach met some internal scepticism from designers. Creating a common product definition in a PLM system somewhat moves power from the designers in the classical engineering domains to the module managers. They are no longer free to design solutions in a decentralized manner; designs now have to conform to module and interface definitions established in the PLM systems.

8.2 Future work

The modular product definition supported by a PLM system has produced promising results in the case study. The work is however still in its early stages, and more research remains to be done. Three major avenues for future research have been identified.

- First, more experience from applying the approach has to be gathered, in order to estimate the value of using it. The aspects to investigate should cover the approach's usability, its applicability, and its usefulness. Such studies could compare product families within and across industries, and link them to performance measures of interest i.e. development time, cost, revenues, quality, etc.
- Second, the study of the application effects of the approach over time should be done. Successive generations of a product family supported by the PLM approach could be described and measured to investigate the aspects of architecture evolution.
- Third, detailing of the version and revisions to the control of structures should be performed— in order to support engineering change management in a more structured way.

8.3 Conclusion

This paper has presented an approach for using a visual product architecture representation in combination with a PLM system for supporting the activities of developing modular product families. The empirical findings in one case do not justify wide generalisations or provide final proof of the suggested benefits. Each product family is used within a different context and with different requirements. As a consequence, different product family approaches exist, each with their own properties. Many factors — a lot of which are of a non-technical nature — determine whether it will be successful in a particular situation. Many preconditions and prerequisites exist for successful implementation of modular product architecture-based development, which have not been described in detail in this paper. Conditions such as e.g. an established IT infrastructure, organisational ownership, sufficient resources/competences, and high-level anchoring and support of the initiatives, are all seen as conditions that have to be in place in companies. The findings, however, carry the formulated hypothesis of creating support when developing modular designs. The findings show that the approach is applicable for development of complex products e.g. members of a product family, with a large number of components, and to a lesser degree as an approach to choose, when developing simple products with few components and simple technology. The approach has been implemented in an industrial setting and the first results by doing this have been described. The most important results are listed in terms of the experienced effects on the modular design process in the company:

- Clearly defined functional systems; an enabler for managing the design process and the responsibility within each system to meet desired properties of the final product. System development supports functionality in components that are spread across multiple modules.
- Clearly defined modules; an enabler for reuse and other reasons for grouping components in modules.

- Clearly defined interfaces; an enabler for reuse of modules and the general overview of interchangeability of modules. Clear allocation of responsibility for interfaces.
- Accurate cost reporting because of automated reporting based on modules.
- Accurate design progress reporting because of automated reporting based on module status.

The main contribution of this research is the distinction between structural and functional contents of architectures, and the ability to handle this distinction when developing product families. By actively using this distinction it is possible to improve modular design, because modularity is based on both characteristics and properties of products. The implemented approach has shown that the benefits are especially dominant in the related CAD system, to represent CAD models in both a functional and physical grouping. One of the objectives for using the Interface diagram in combination with a PLM system is to enable parallel activities in different life phases. Parallelism in design activities requires carefully decomposing products into discrete modules and specifying interfaces to ensure that the results of the parallel activities go hand in hand.

Last, it is important to note that any products could potentially be modularised and their information could be managed in PLM systems, but to benefit more easily from the advantages of PLM systems, companies must be selective in choosing which products to support with this approach. The strength in this approach is its ability to address complex products with a large number of components, components belonging to different technical domains, and/or components developed by different organisational teams. To apply this approach to simple products with few components could be characterised as “killing butterflies with muskets”.

8.4 Acknowledgements
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ARTICLE 6 PRODUCT PLATFORMS AND MANUFACTURING STRATEGIES

Utilizing Product Platforms in Industrialized Construction

Submitted to the “Journal of Construction Management and Economics”

UTILIZING PRODUCT PLATFORMS IN INDUSTRIALIZED CONSTRUCTION

Bonev, Martin; Wörösch, Michael; Hvam, Lars

ABSTRACT

Purpose – Offering custom tailored buildings at reasonable costs has been a growing concern to many construction companies. A promising approach adapted by operations management and design theory regards individual building projects as the adjustment and recombination of components and processes from a set of predefined platforms, while configuration systems assure feasible building solutions. The aim for of this paper is to explore the development of a platform-based project execution in the industrialized construction sector, with a focus on systematically balancing for cost and value.

Design/methodology/approach – After adjusting some of the underlying assertions of platform design to the engineer-to-order situation in construction, the practical implications are evaluated on a case study of a precast manufacturer using high performance concrete.

Findings – Based on empirical findings from three distinct platform strategies, this research highlight key aspects of adapting platform-based developed theory to industrialized construction. Building projects employ different layers of product, process and logistics platforms to form the right cost-value ratio for the target market application, while modelling methods map structural platform characteristics so as to balance commonality and distinctiveness.

Originality/value – This paper is an initial attempt towards a theory on platform-based development in the industrialized construction sector, which goes beyond concurrent approaches of standardizing and systemizing of buildings projects. It adapts and extends existing frameworks for platform development to the engineer-to-order situation in construction and empirically validates their cost and value effects.

Keywords: Industrialized construction, Engineer-to-order, Platform, Mass customization, Value

Paper type: Case Study

INTRODUCTION

Various attempts have been made to meet up with the diverse challenges in the building sector. Off-site manufacturing and the creation of systematic procedures and standardized building elements enforced the industrialization of the sector already in the middle of the nineteenth century (Finnimore, 1989). Zabihi et al. (2013) for example, argue that with off-site manufacturing, capacity and quality could be increased, while simultaneously offering more complex building components at a lower cost. Time related advantages with regard to the production and erection of buildings are for instance discussed by Sacks et al. (2004) and Jaillon and Poon (2009). Other potential improvements involve the reduction of construction waste (Lachimpadi et al., 2012) and a lower environmental impact as well as higher sustainability performance (Chen et al., 2010).

The delivery of industrialized building systems has more recently been seen as a means for additional productivity advancement (Jansson et al., 2013; Thuesen and Hvam, 2011). The building is seen as a set of major systems like walls, roof and foundation, where enterprises within on-site erection and off-site production of products and components mutually contribute to the construction project (Lachimpadi et al., 2012). Thuesen and Hvam (2011) for example investigate how system deliveries can lead to efficiency improvements of the German on-site construction. Their study shows how standardized procedures, preferred building solutions, as well as the reuse of experience and working groups (logistics platforms) have accomplished significant cost reductions on a number of housing projects without sacrificing any customer value. Similarly Jansson et al. (2013) study the advantage of delivering of systems building as opposed to individual components. The authors examine the reuse of common processes and technical solutions across a number of building projects. Their effect on the design phase of two case companies has further been discussed in relation to the platform categories defined by Robertson and Ulrich (1998).

Competing with building systems which share common platforms provides a promising alternative to the merely standardization strategy of traditional industrialized construction. Apart from systemizing procedures and reusing technical specifications, in many industries the multi-product strategy of a platform approach has led to additional productivity and flexibility advantages. Early contributions see companies' product structure as a main driver for a platform implementation, emphasizing the definition of a product platform (Meyer and Lehnerd, 1997). Baldwin and Clark (2000) define three characteristics of a product platform as: (1) a modular architecture, (2) the interfaces, and (3) the standards, which form design rules to which the modules conform. The prevailing approach to platform development is therefore to develop methods, tools and algorithms in support of the physical product family modeling(Yigit et al., 2002). Moreover, Robertson and Ulrich (1998) point out that product platforms represent more than the physical structure of the product, but rather a collection of assets which are common for a set of products. This holistic view has also been discussed by Jiao et al. (2007). The authors argue that a platform design can be seen as defining a set of common elements along the entire value creation process of a product or project respectively.

Research aim

The aim of this research is therefore to explore the potential of a platform-based product development approach within industrialized construction, in particular represented by the precast sector as a major actor within the industry (Sacks et al., 2004). The remaining of this paper is formulated as following. First, existing platform frameworks are adapted on the engineer-to-order (ETO) situation of the precast industry. A heuristic view to platform design and modelling for building projects is introduced and its impact on the precast value chain is discussed relative to different manufacturing strategies. Next, a case study of a precast concrete manufacturer is presented, where the proposed methods are being applied and their operational impact on the precast value chain is being discussed. The paper concludes with the benefits and limitations of the proposed approach.

CUSTOMIZING BUILDING PROJECTS WITH PLATFORMS

Research in construction has a long tradition in comparing and adapting related approaches from other industry sectors, like car production. Several authors have investigated the potential such of cross-industry learning, where clear benefits on industrialized housing could be proven (Barlow et al., 2003). A key lesson from the automotive industry is the ability to provide a higher degree of customization without compromising lead times, quality and costs (Parry and Graves, 2008). What became known as mass customization aims at using configuration systems, adjustable product structures, flexible processes and adaptive organizations around a predefined set of platforms to efficiently offer custom tailored products (Su et al., 2005). To explore the potential for platforms, manufacturing companies are classified according to the customer order decoupling point (CODP), i.e. the degree the manufacturing set-up is customer-independent and based on forecast or order-related and connected to a specific sale (Sharman, 1984). Wikner and Rudberg (2005) categorized the most commonly mentioned strategies throughout literature as engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS). In the context of construction, concept-to-order (CTO) is in addition used to describe a situation in which a customer is strongly involved already at the early conceptual phase of a building project (Winch, 2003). Taking the example of a building, by engaging with e.g. the architect, in a CTO situation the customer then actively shapes the conceptual building scheme from the beginning, without in particular basing his ideas on a predefined structural or feasibility concerns (Mora *et al.*, 2008). Empirical examples can be found in one-off projects, where uniqueness of design is more important than productivity or functionality (Hobday, 2000). In a MTS strategy on the other hand the customer enters the process at a very late stage of its value creation. This strategy makes use of market forecasts to convert raw materials and components all the way to final standard products in accordance with expected customer demands. Between those two categories there are MTO and ATO firms which allow a certain degree of customization based on the standardization level of their products, like e.g. the previously mentioned car manufacturers.

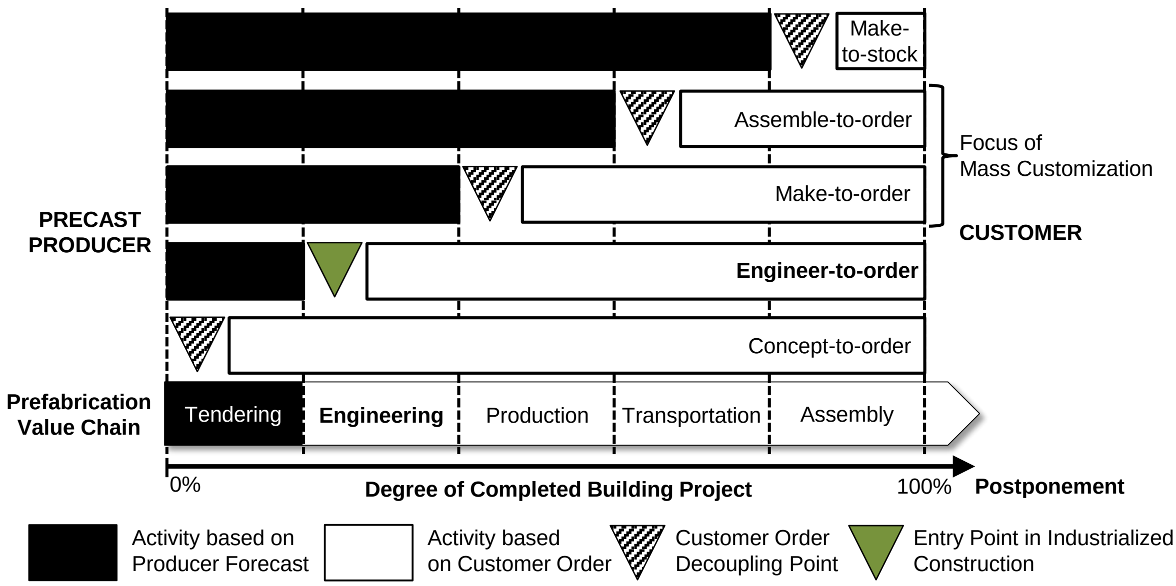

Figure 1: The CODP model in relation to the value chain of a precast manufacturer

In relation to the CODP, the precast supplier can be classified as an ETO manufacturer providing industrialized building systems (Zabihi et al., 2013). As a common characteristic for ETO firms, the value chain consists of non-physical stage involving marketing, tendering and engineering activities and a physical stage which concerns production, transportation and on-site assembly (Bertrand and Mu, 1993). The schematic representation in Figure 1 indicates how the customer enters the engineering phase of the value chain after completing the tendering process for a project. Starting from there, all subsequent phases including i.e. producing the concrete elements, shipping and assembling them on the construction site, can be directly related to a particular customer or client order.

To achieve mass customization, companies coming from a MTS strategy need to move towards an ATO production (Wortman et al., 1997). On the other hand, ETO companies need to accept a higher level of product and/or process standardization, while postponing the COPD further down the value chain (Haug et al., 2009). In avoiding this tradeoff and moving the equilibrium point to a higher flexibility and productivity level, companies are utilizing platform concepts to balance the required level of standardization, while maintaining the desired flexibility throughout the value chain (Jiao et al., 2007). Hence, a key objective of a platform-based product development is to provide sufficient product variety to meet individual customer needs while maintaining economies of scale and scope within manufacturing (Pine, 1993).

PLATFORM MODELLING FRAMEWORK FOR BUILDING PROJECTS

Figure 2 illustrates a holistic approach to product family design through platforms throughout the value chain of a building project. The framework comprises five domains; customer, functional, physical, process, and logistics domain. The customer domain involves the development of customer insight, where marketing techniques are used to determine customer attributes (CAs), i.e. requirements in relation to the market (Meyer and Lehnerd, 1997). Apart from requirements directly coming from the customer, there are a number of stakeholder requirements and governmental regulations that need to be fulfilled as well (Stevens and Martin, 1995). For ETO firms the nature of the requirements tends to be specific and technical (Rahim and Baksh, 2003). In the building sector they are often related to the building design and its different levels of details (Kiviniemi, 2005). As building regulations evolve, house builders and off-site manufacturers have to keep compliance and quickly adapt to new demands (Pan et al., 2007). Once identified, common requirements can be grouped together to form consistent value prepositions for different market segments and to grade the impact the stakeholders have on them (Simpson et al., 2011). CAs are then converted into a minimum set of functional requirements (FRs) in the functional domain as *CAs=min({FRs})*. Here architects traditionally work out building concepts from the customer information in an architectural design based on existing industry norms and standards and available product technologies. The architectural design includes overall parameters of a building and architectural preferences on e.g. materials, shapes and styles, or increased energy efficiency. In platform terms this mapping constitutes the definition of a product portfolio with a number of product families through which common practices of order configuration and sales automation with configuration systems are performed (Jiao et al., 2007).

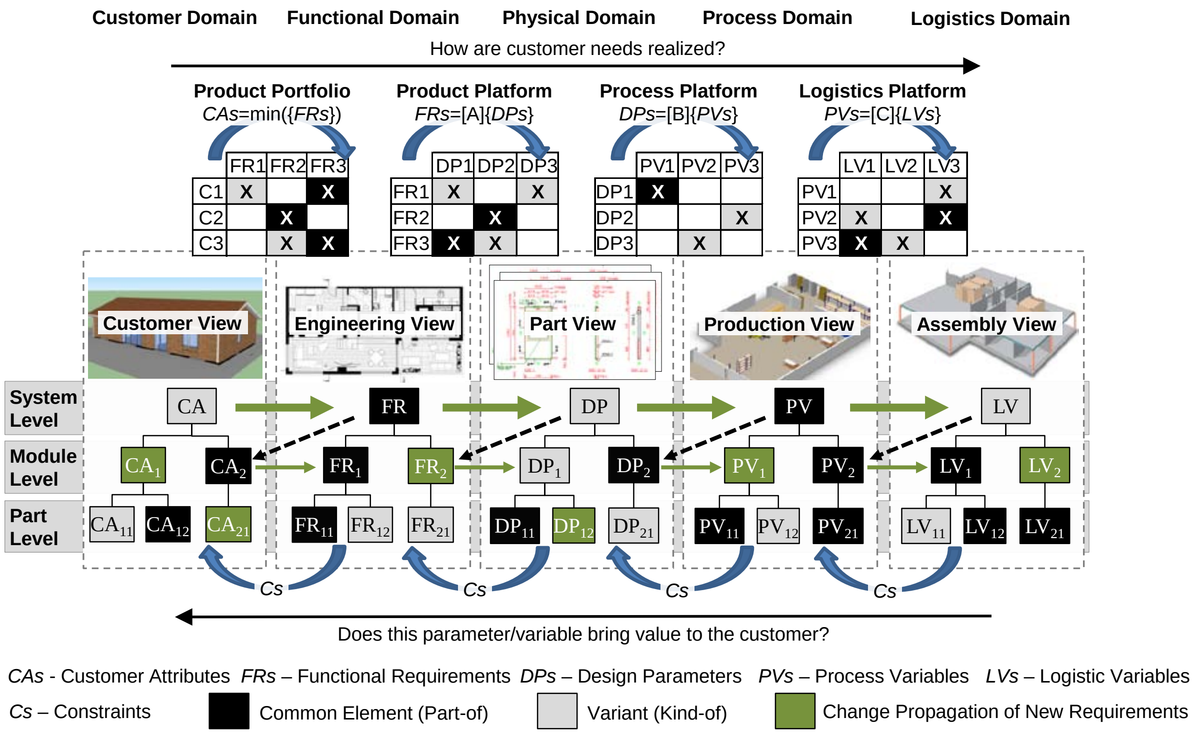

Figure 2: Holistic view on platforms in industrialized construction (adapted from Jiao et al., 2007)

Mapping the relationships and interfaces of FRs to design parameters (DPs) is done in the physical domain and compasses the definition of a product architecture as *FRs=[A]{DPs}* (Suh, 2001).

Engineers transfer the initial design intent of the architect into a structural model with the objective to create feasible structure solutions, while referring to given architectural patterns and constrains. Such decisions are mostly based on the engineer's knowledge and experience of the realization of the design intents on a given situation. With the structural analysis and the determination of the building behavior of the preliminary design, the design focus changes from the innovative design intent of the conceptual design to a design task on a routine basis (Mora *et al.*, 2008). A process architecture can accordingly be defined as the mapping of the DPs to process variables (PVs) in form of *DPs=[B]{PVs}* and logistics variables (LVs) as *PVs=[C]{LVs}* respectively. The last two domains traditionally involve the creation of common manufacturing processes, production technologies and distribution networks (Meyer and Lehnerd, 1997). Common production tools, machines, transportation resources and assembly methods can be used to reduce manufacturing set-up risks and to reuse proven production and assembly processes (Sawhney, 1998). From a precast perspective, the main concern is to transform of design specifications of a building into physical precast elements and their subsequent on-site assembly.

In an ETO situation developing well-functioning relationships among teams and team members is particularly important. Sales, engineering and production activities are traditionally hardly standardized and rely on specific skills and craftsmanship. Extended coordination mechanisms are therefore used to balance product specifications with engineering and production capabilities for all upcoming orders (Konijnendijk, 1994). In using stable teams within each stage of the value creation of a building, the precast producer can expect to benefit from economies of scope. The ability to produce and deliver the created building designs results in constraints (CSs) which have an upstream effect on the foregoing domains. Precast elements for example need to be lifted and assembled at the construction site. Build-in lifting brackets and mechanisms for assembly have to be designed and cast in place at the foregoing steps of the product realization process.

Modelling platforms from different perspectives through the so called views facilitate the consideration of all five domains of a building project (Jiao and Tseng, 1999). As indicated in Figure 2, generic modeling notations are commonly used to represent hierarchies, commonalties (Part-of structure), alternative varieties (Kind-of structure), and ranges (Jiao and Tseng, 1999). Change propagation effects from newly identified building requirements can then directly be seen within the system (Clarkson *et al.*, 2004). The hierarchical classification of materials, parts, components and subassemblies represents the product structure (Do *et al.*, 2002), and is consistent with the common definition for bill of material (BOM) (Garwood, 1988). The different perspectives and relationships are modeled with the same notation, while their interrelations are mapped through direct connections and constraints for configuration. Most generic modelling approaches follow the basic principles of object oriented modeling using the Unified Modeling Language (UML) (Felfernig *et al.*, 2000). With their help, even complex product architectures, such as for ETO products can be created (Brière-Côté et al., 2010). Existing product lifecycle management (PLM) solutions today obtain the same object oriented hierarchical structure of a product (Mesihovic *et* *al.*, 2004). To maintain the overview of product structures with many component interrelations, matrix-based modelling methods have been developed (Steward, 1981). Elements are simply listed in columns and rows and connections are made through the matching cells. Over the years, many related modelling methods and tools have been proposed in academia. With their relatively simple notation, Design Structure Matrixes (DSMs) have e.g. been developed to assess, reorganize, and cluster relationships between functional or physical elements (Eppinger *et al.*, 1994). The methods have been applied on a number of product examples spanning from commercial to industrial products. To represent hierarchies of common and distinct elements in ETO platform designs, the matrix-based models are to be combined with the generic modelling techniques.

PLATFORM EFFECTS ON ENGINEERING

ETO firms are by definition strongly concerned with engineering activities and how they are to be carried out in combination with manufacturing (Konijnendijk, 1994). To achieve the benefits from the use of platforms, they have to postpone the CODP to a later stage of the value chain, or in other words they have to accept a higher degree of predefinition of the subsequent tasks. Wikner and Rudberg (2005) point out the two-dimensional character of postponement for ETO firms. Apart from the production dimension, postponing the CODP can be seen from the engineering perspective as well. Based on contributions identified in literature, the authors conceptualize the extended two-dimensional framework of the CODP and further describe the characteristics of a possible engineering-production mix in terms of postponement. Precast manufacturers are traditionally characterized as being engineer-to-order in the engineering dimension (ETO_{ED}). They use the majority of their engineering resources for making building specifications on individual projects, while complying with industry specific standards and norms. Their products obtain a low number of commonality, as the solution space communicated to their customers contains no explicitly formulated boundaries in form of e.g. catalogues from the beginning. Figure 3 depicts the link between the degree of standardization from a building system perspective and its potential impact on placing the CODP in engineering.

The lowest level of system standardization, i.e. formalization, targets the part and component level. From a precast perspective such components are e.g. represented by different forms and dimensions of iron bars, insulation materials, concrete recipes etc. The formalization process includes the creation of a formal product family model containing generic product structures of the domains. Through product development, precast manufacturers need to agree on a common solution space for their product families, where e.g. possible precast element dimensions, load bearing capacity, dimension and placement of recesses, or different materials and surfaces mapped. The objective of this stage is to make an explicit documentation of possible variations, calculations and restrictions for a given family, without necessarily reducing the functionality and respectively the variety given to customers. By formalizing the product portfolio, the precast producer is able to reuse the product knowledge for each building project more systematically and adapt-to-order (ATO_{ED}) the building specifications within the boundaries of the established solution space. Knowledge-based engineering (KBE) systems can then be used to integrate formalized technical product knowledge with the order fulfilment process and thus promote gains from knowledge reuse and sharing (Stokes, 2001). In literature several attempts to increase organizational capabilities within the construction sector through IT system support can be observed, like e.g. demonstrated by Udeaja et al. (2008), Rezgui (2001) and Nitithamyong and Skibniewski (2004). In a ATO situation so called product configuration systems are used to streamline the sales and quotation process of customized goods in satisfying the term *CAs=min({FRs}* (Salvador and Forza, 2004). For ETO sectors such systems are moreover helpful to partly automate some of the subsequent engineering activities in assistance of *FRs=[A]{DPs}* (Hvam *et al.*, 2008). However, comparable achievements in coordinating the specification process in construction have not yet been reported.

In level 2 standardization engineers may define a standard set of building modules or subsystem variants, like different types of facades, which can be commonly used within the precast families. The different modules and subsystems would be reconfigured for each building project through a configure-to-order (CTO_{ED}) approach. At level 3 standardization finally refers to the development of entire standardized buildings or building systems, as e.g. a predefined set of walls to an entire house type. Since all product specifications for a building project are defined prior to the actual customer order, this strategy can be characterized as engineer-to-stock (ETS_{ED}). Companies offering houses from a type house catalogue are a good example for an ETS_{ED} strategy. The focus of using product platforms for mass customizing buildings lies between the continuum of ETO_{ED} and ETS_{ED}, where the precast manufacturer accepts a certain level of product adjustments on a module or part level in the design based on individual customer needs. Empirical examples within related industries, such as for mass customized timber houses, can for example be found in the Japanese housing market as discussed by Gann (1996).

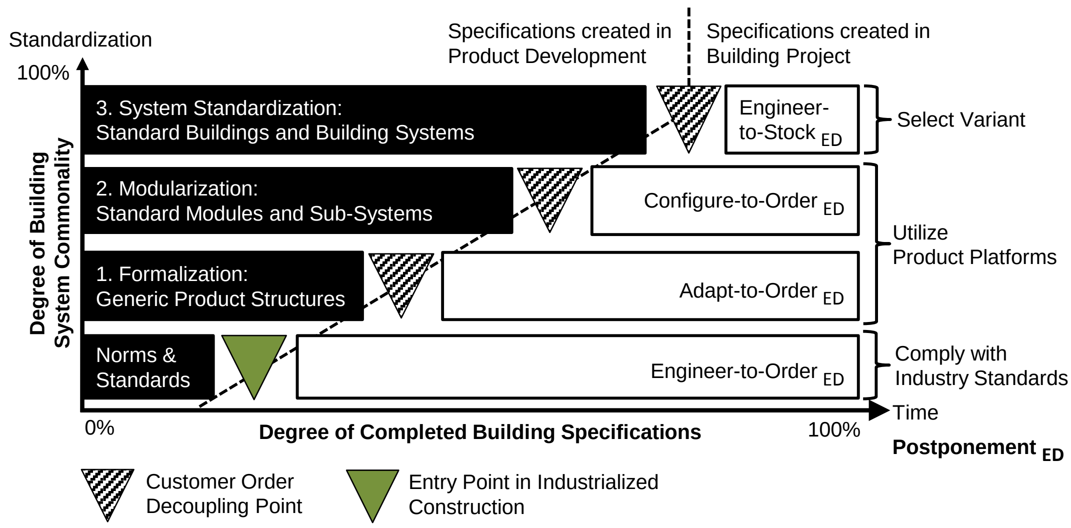

Figure 3: Leveraging the platform strategy through different decoupling points in engineering (adapted from Hvam et al., 2008)

COMBINED PLATFORM EFFECTS ON THE PRECAST VALUE CHAIN

As argued by Wikner and Rudberg (2005), several feasible interrelations of a combined engineering-production CODP-mix can be defined. Figure 3 illustrates how two dimensional placement of the CODP can be applied to the building industry. Precast firms are traditionally utilizing a craft production approach in form of ETO_{ED} combined with a make-to-order in the production dimension strategy (MTO_{PD}), or in short a [ETO_{ED}, MTO_{PD}] strategy. In contrast, the ETS_{ED} strategy of type house providers is used in combination with the MTO production dimension as [ETS_{ED}, MTO_{PD}]. Even through for type houses all building specifications are already defined in the product development phase, the production of e.g. walls would not start unless an order has been placed. According to the CODP definition, mass produced buildings with a [ETS_{ED}, MTS_{PD}] strategy would be created entirely based on forecasts, in other words they would be pushed to the market without any consideration from customers or clients. As displayed in Figure 4, the mass customization area covers the remaining mix of feasible engineering and production mix approaches. The Japanese timber house market can be used as an analogy for the empirical evidence of the proposed strategies. Sekisui House for example follows a so called “tailored standardization” approach with an [ATO_{ED}, MTO_{PD}] strategy. The company uses standard components which are mainly produced on demand and adopted to customer requirements. The on-site assembly is done by specially trained subcontractors. Another mass customization example in construction is represented by Sekisui Heim. The company makes use of a “standardized customization” strategy through a [CTO_{ED}, MTO_{PD}] approach, where standard modular steel- and timber-frames around rooms are created off-site only few days before delivery. The modules are then directly shipped to the building sites for further assembly. An example for a [CTO_{ED}, ATO_{PD}] strategy can be found on Toyota Homes. The company utilizes a so called “segmented standardization” approach, which is comparable to Toyota’s car production. Modular units are produced based on forecasts without any significant input from customers. Customization is then performed in the on-site assembly process, where modules are recombined and adjusted to particular housing needs (Gann, 1996). All three approaches make use of process and logistics platforms to significantly reduce the time and resources for manufacturing and on-site assembly. According to Gann (1996), with 50% less labor cost for the on-site assembly process, by having building modules, up to 55% assembly lead time compared to traditional pre-fabricated panel houses and up to 67% compared to a carpenter-built building are being saved. At the same time, the companies combine a high degree of tailoring from their customers and clients with a stable delivery quality. They utilize of-site manufacturing practices, which are comparable to assembly lines in other industries to achieve the required productivity.

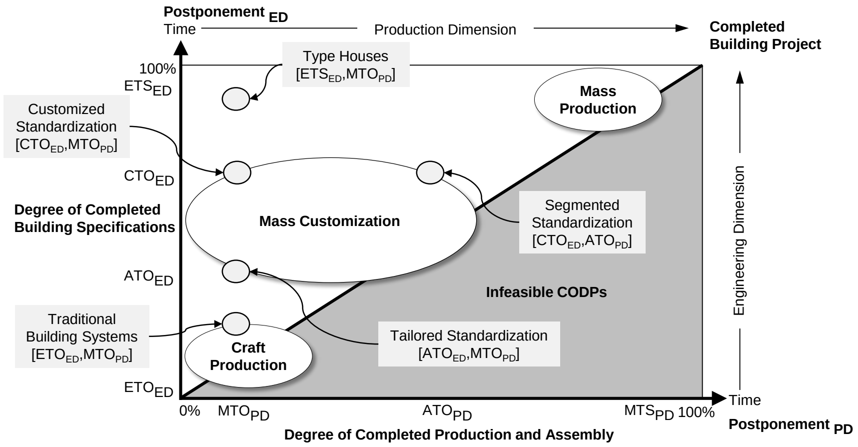

Figure 4: Leveraging the platform strategy through a two-dimensional placement of decoupling points (adapted from Rudberg and Wilkner, 2004)

RESEARCH METHODOLOGY

To explore the applicability of platforms in the precast industry, we use a single case study approach on a precast concrete manufacturer as described by Voss (2002). This study is a part of a broader research project focusing on developing innovative and sustainable building materials, manufacturing processes and improved transportation, and assembly practices in industrialized construction. The case company is a consortium of two separate companies – an architecture firm and a precast concrete manufacturer – offering precast sandwich elements and foundations traditionally for the Danish market. The joint venture was established with the purpose of developing the engineering, production, and assembly of pre-fabricated high performance concrete (HPC) elements.

In total 45 supporting research interviews from 35 interviewees were conducted between 2011 and 2013 at the case company, its stakeholders and collaborating industry experts. As literature within construction on this topic remains vague, the purpose of the interviews was to gather additional empirical insight into the applicability and impact of platform based product design of precast elements on the industrialized building sector. A particular focus was laid on the practical implementation of the platform framework, including the discussed modelling methods for platform design. As there are special rules for how to structure, conduct, and interpret qualitative research interviews, guidelines provided by Girmscheid (2007) were applied. Each interview was semi structured, to allow the flexibility of gathering additional insight throughout the interview process. The variety of professions, such as project management, structural engineering or marketing, enabled a more consistent coverage of the entire value chain. The results gained from the interviews served as a starting point for subsequent analysis of the platform approach as well as a feedback mechanism for the development progress. In addition to that, the researchers were given access to all project data, such as project offers, production drawings, and cost figures within the stated time period of two years. The impact of the platform use for the HPC product family was compared to the use of traditional concrete elements that are produced by precast manufacturer, where data from 45 projects performed in 2012 of traditional concrete elements and 6 projects from 2011 to 2013 with HPC products was investigated. The inspected data was triangulated against the conducted interviews, where in a second round mismatches were addressed. The overall research design was in part exploratory and the obtained results are not intended to be generalized for the entire building industry.

ANALYSIS AND RESULTS

Formulating the high performance concrete portfolio

The development of the HPC product portfolio was initiated in 2010. Working on new concrete recipes, the organisation intuitively realized that many of the building challenges in developed and developing markets could potentially be addressed by using HPC as an alternative to e.g. the traditional concrete, plaster or wood materials already existing on the market. The company made an initial investigation on a number of markets both in Northern Europe as well as in developing markets in the southern part of Africa from a customer perspective. A series of CAs where formally listed, grouped and graded. A five scale approach as defined by Martin and Ishii (2002) with 1) least important and 5) very important was used to derive general requirements from the CAs into concrete DPs. Moreover, the CAs' potential for propagation of changes within the system was graded based on the stakeholders' subjective preferences (Clarkson et al. 2004). From the initial grouping of the requirements, three different distinct product families could be formed: a High-End, a Re-insulation and a Low-End building system (Figure 5).

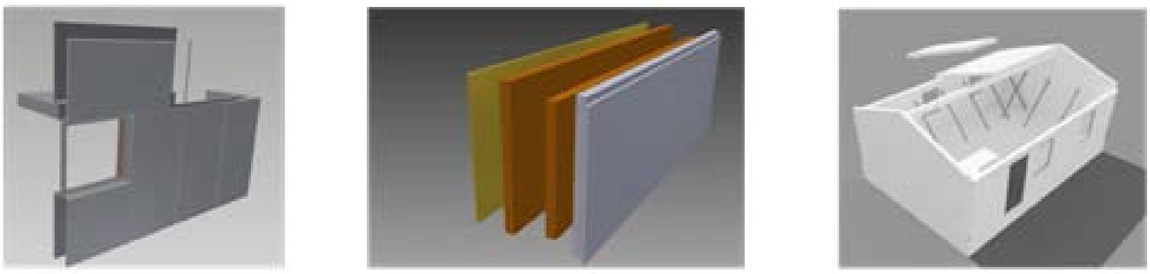

Figure 5: High performance concrete product portfolio: Re-insulation, High-End and Low-End system

Figure 6 displays the high-level list of CAs, the characteristic value proposition for each product family where the product family names indicate the intended market application. The design of the HPC High-End solution is closer positioned to the traditional elements. It targets the high-end market segment for customers who are concerned with buildings that obtain a unique surface design and aesthetics, better insulation, increased space optimization as well as reduced CO_2 emission. The Re-insulation system aims at competing with established products using metal or wood for re-insulating existing buildings. It utilizes the same HPC material for offering re-insulation panels that, compared to existing solutions, have a longer life-time, an improved surface design and variety, low operation cost, and which are easy and cheap to assemble. The third building system targets the low-end market segment of shack dwellers, which are predominately to be found in developing markets. Based on the same HPC technology, this solution provides stable and long-lasting buildings with a reasonable quality at a competitive price and thus suggests a fundamental alternative to existing low-end housing today. Due to the special requirements for this market segment (Ofori, 2007), the Low-End system is emphasizing a strong focus on using local and often unskilled labor, cheap and simple production with predominantly local material, and a simple and quick on-site assembly. This clear value proposition allowed the engineers to focus on aspects within each building system which generate a direct value to the customer, while limiting the non-value adding activities.

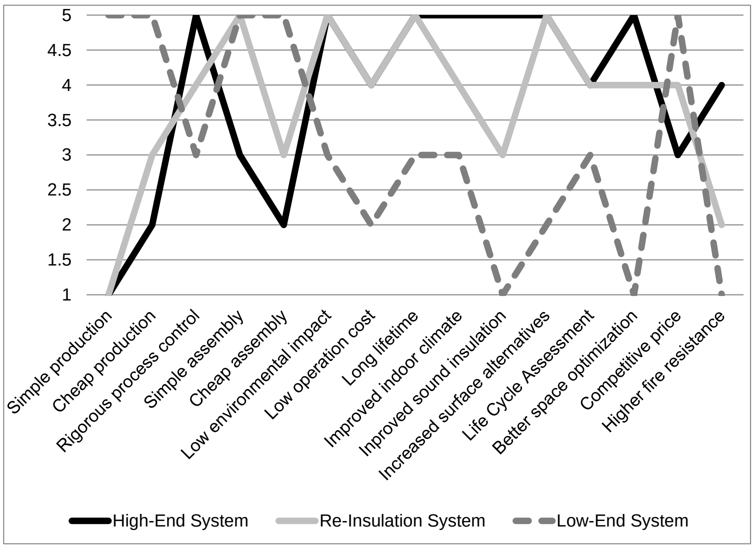

Figure 6: Value proposition of the three product families with evaluated customer attributes

With the initial value definition for each product family, the design of the building systems was created in a close collaboration between architects and engineers. To compare the similarities and differences between the families, we use the traditional precast products as threshold values representing the current market norms for the industry. The result of the comparison is summarized in Table 1, where for each product family the heuristic approach to platforms has been applied. The different views of the building system where modelled according to the generic modelling methods introduced by Hvam et al. (2008), while intra-domain matrixes where used to connect views.

The product platforms used in the high performance concrete portfolio

The High-End HPC system consists of sandwich elements and their connection to each other and to other building systems, such as to foundation or ceiling. From an engineering perspective, their modified concrete recipe obtains a number of functional advantages compared to the traditional concrete elements, which facilitate fulfilling the objective of *CAs=min({FRs})*. In addition to an altered concrete material, a longer building lifetime has been obtained through a new jointing system made from stainless steel. From a part view, with the High-End system the company focused on the value adding variety on the component level, while preserving the flexibility to meet all customer demands within the target market segment. Compared to traditional concrete elements, the High-End system uses fewer variants for reinforcing, insulating and connecting the sandwich elements, resulting in an overall higher part commonality of the system.

The Re-Insulating system utilizes the same HPC material as the High-End solution. To conform with the requirements (FRs) of the re-insulating market, several additional DPs have been added. Instead of having a back plate made from concrete, a second layer of insulation material has been attached to the elements. A new mounting system ensures the fixation of the elements to the existing building, while a simpler jointing solution made out of stainless steel has been developed to seal the surface of the system. The Re-Insulation elements consist of a limited number of modules coming in different sizes. To ensure a high degree of flexibility, all modules use the same mounting and jointing system and can be combined and exchanged without affecting each other. Since the HPC material is more costly compared to the competitive products on the market made out of wood or metal, to reduce the cost of the each element, unnecessary variety of the remaining parts has been lowered considerably. However, compared to the existing market standards the additional variety of surfaces ensures the high aesthetic value of the overall re-insulation. For the Low-End system on the other hand flexibility is less important than the price. As all HPC building systems mainly share the same raw materials, the company has to focus on standardizing the Low-End system as much as possible. It uses two different element types, roofs and surfaces in combination with common components to create entire buildings at a competitive price. The shape and size of the buildings can be modified, as elements can be moved, recombined or additional ones can be attached.

Table 1: Overview of the platform strategy of the high performance concrete portfolio in relation to traditional precast elements

Dimension	Traditional Precast	High-End System	Re-Insulation System	Low-End System
Product Portfolio	Market average requirements for aesthetic, insulation, space optimization, lifetime and environment	High requirements for aesthetic, insulation, space optimization, lifetime, quality and environment; low requirements on price, easy production and assembly	High requirements for insulation, lifetime and assembly and space optimization; moderate requirements for aesthetic and price	High requirements for surface design, easy and cheap production and assembly; moderate requirements on lifetime and environment; low requirements for aesthetic, insulation and space optimization
Product Platform				
Engineering View	Traditional concrete recipe, market norms for strength, load-bearing capacity, heat and sound insulation, lifting	High performance concrete, increased capabilities in strength, load-bearing capacity, lifetime, heat and sound insulation, reduced CO2 emission; redesigned joining system	High performance concrete with the same characteristics as the high-end system; redesigned insulation, joining and mounting system	High performance concrete with the same characteristics as the high-end system; redesigned joining and mounting system to other buildings
Part View	Part commonality at market norms; iron mesh with limited variety, multiple shear connectors, insulation materials, reinforcement, recesses, concrete recipes and surfaces	Increased commonality in element dimensions, common iron mesh, two shear connectors, two insulation materials, limited reinforcement, common concrete recipe, alternative additional surfaces and joining elements	Few common element dimensions, common fiber mesh, common mounting system to walls, two insulation materials, common reinforcement and concrete recipe, few surfaces, common joining elements	Two common element dimensions, common fiber mesh, shear connector, insulation material, reinforcement, recesses, and concrete recipe, two surfaces and roofs, common joining elements
IT Support	No specification process support	No specification process support	No specification process support	No specification process support
Process Platform				
Production View	Flexible processes, little mold commonality	Flexible processes, little mold commonality	Limited process flexibility, high mold commonality	Limited process flexibility, very high mold commonality
Team Members	Unstable relationships	Stable relationships	Stable relationships	Stable relationships
Handover Process	Little quality control, no formal handover procedures	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries with less strict sub-delivery
IT Support	Inconsistent data collection, no systematic learning	Centralized documentation, i.e. measurements, observations, sensors, tagging, quality control, central database	Centralized documentation, i.e. measurements, observations, sensors, tagging, quality control, central database	Centralized documentation, optional quality control
Continuous Improvement	Long-term cycles	Short-term cycles	Short-term cycles	Mid-term cycles
Logistics Platform				
Transportation	Little space utilization due to weight restrictions for trucks	High space utilization due to 50% less volume and 70 % less weight	High space utilization, comparable to re-insulation market norms	Maximum space utilization with smaller trucks, due to 80-95% less volume and weight
Assembly View	Crane size and assembly process according to market norms	Smaller cranes due to reduced element weight, higher requirements during assembly process	Smaller cranes due to reduced element weight, fast assembly process with standardized tooling, no scaffolds	Small cranes, more than 50% less assembly time with standardized tooling
Team Members	Unstable relationships	Stable relationships	Stable relationships	Stable relationships
Handover Process	Little quality control, no formal handover procedures	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries with less strict sub-delivery
Continuous Improvement	Long-term cycles	Short-term cycles	Short-term cycles	Mid-term cycles
Postponement Strategy	ETO_{ED}, MTO_{PD}	ATO_{ED}, MTO_{PD}	CTO_{ED}, MTO_{PD}	CTO_{ED}, MTO_{PD}

The process platforms used in the high performance concrete portfolio

In construction terms the HPC product platforms exhibit a rather radical degree of redesign compared to the traditional concrete elements. From a production perspective this difference is less obvious, as all three HPC building systems mainly go through the same production steps as the traditional elements. Yet, a cost and time advantage is achieved through reusing already existing production facilities, machineries, equipment and labor. Additional benefits arise with the higher degree of part and module commonality of the HPC portfolio, resulting in less flexible but at the same time more reliable and stable production steps. While for the High-End solution the effect from increased part commonality is smaller, the Re-insulation and Low-End elements strongly benefit from the standardization attempts on the module level. Through the limited variety in dimensions, the company reuses a set of standardized molds for casting and recesses made out of steel, thereby reducing waste and the need for resetting the production. Furthermore, the thinner dimensions and sharper edges of the HPC elements result in smaller production tolerances. To meet the increased quality demands when working with HPC material, stable and well trained teams have been created along with well-defined handover procedures for process deliveries. The high quality standards are ensured with additional IT support for measuring, monitoring and tracking the entire production. A central data base has been installed to collect and evaluate the collected information. This constant quality control has led to shorter continuous improvement cycles of the HPC products and the way how they are produced.

The logistics platforms used in the high performance concrete portfolio

A major advantage of using HPC instead of traditional concrete recipes is the reduced dimensions and weight of the elements. Transportation costs of the elements are typically responsible for 10% of the cost for the entire building system. Therefore reducing the costs of shipping the elements can have a big impact on the overall profitability of the building projects. This effect is exemplified on the High-End system. Here, the HPC sandwich elements have 50% less volume and up 70% less weight compared to traditional precast elements. In result the company is able to better utilize the space of the trucks that are used for shipping and have considerable savings during assembly, which would otherwise be restricted by the weight of the elements. In developing markets the reduced volume and weight of the Low-End building system even accounts for 80-95%. Smaller and lighter elements in turn make it possible to transport the elements with smaller trucks even through rural and unpaved areas. Another factor contributing to a lower price is the fact that fewer variants of the product are offered based on the Low-End product platform. From an assembly perspective the volume and weight reduction of the HPC portfolio means that the company can operate with smaller and cheaper cranes at the building site. Moreover, with the Re-insulation and Low-End solution, the case company has introduced a new fast and simple assembly process, where standardized tooling is utilized for the entire on-site work. Apart from the benefits coming from smaller and lighter elements and standardized processes, a strong emphasis is being set on the employees and the quality of delivery. Comparable with the process platforms, stable and specialized teams are making sure that the predefined deliveries and all handover processes are being kept. Besides, the increased transparency during assembly leads to shorter feedback cycles; allowing the company to continuously improve their procedures in shorter terms.

Platform effects on the high performance portfolio

The platform analysis of the HPC portfolio demonstrates the potential advantage of focussing on the right balance between commonality and distinctiveness within each view of a product family. For the case company an increased reuse of building specifications, machineries, tools and processes created in the development phase resulted in a higher degree of commonality along the value chain of a building project. Compared to a traditional precast project, an increased reuse capitalizes in the ability to delay the differentiating activities of each project. Figure 7 depicts the postponement strategy of the three HPC product families. Depending on the intended positioning in the market, each product family is using the platforms to a degree, which allows placing the two-dimensional CODP according to the optimum cost-value relation. A traditional building project at the case company today requires in average three hours of engineering work per concrete element, once the detailed design of a building has been finalized. Having invested in formalizing its offerings to the market, the High-End system on the other hand adapts systematically the building specification created during product development to the individual requirements of a project with a [ATO_{ED}, MTO_{PD}] strategy. The firm operates with the ATO_{ED} strategy within the boundaries of the assigned solution space in engineering, allowing for a higher level of flexibility in the subsequent production and assembly. While ensuring the desired delivery quality, the company strives in gaining economies of time throughout the specification process of the building, saving up to 20% of engineering time for completing the building specifications. The effect of increased reuse of building specifications is even stronger for the Re-insulation and the Low-End system, where up to 80% of the overall engineering time is being economized. Both systems utilize a [CTO_{ED}, MTO_{PD}] approach, in which the benefits of having standardized modules take effect already at the conceptual design phase of the project. Even though formal product architectures have been established, at the time of our study the case company has not invested in establishing a configuration system for any of their products. With the planned implementation of IT, additional positive lead time effects in engineering are expected.

The higher level of commonality along the entire life cycle of the building project directs to additional reductions of lead times within production and on-site assembly. The additional benefits from using the platforms can be exemplified on the Low-End system, where the standardized production processes report a 30-50% lead time reduction. The redefined on-site assembly allows the company to use standardized tooling combined with lighter and smaller elements to assemble a single family building with three workers and one single tool in merely seven hours after having casted the foundation. With the ability to deliver quick and cheap housing, the company aims at directly addressing the growing housing demand in developing regions. As indicated in Figure 7, once access to new markets has been gained, scale-up programs are planned to increase the productivity of factories. By moving from a [CTO_{ED}, MTO_{PD}] towards an “IKEA”-like [CTO_{ED}, ATO_{PD}] strategy, the different wall elements can then be produced based on a forecast, reducing the delivery time of the building to the lead time of transportation and assembly. While staying within the boundaries of the building system, each customer is then able to order his configured house, based on an individual combination of the elements.

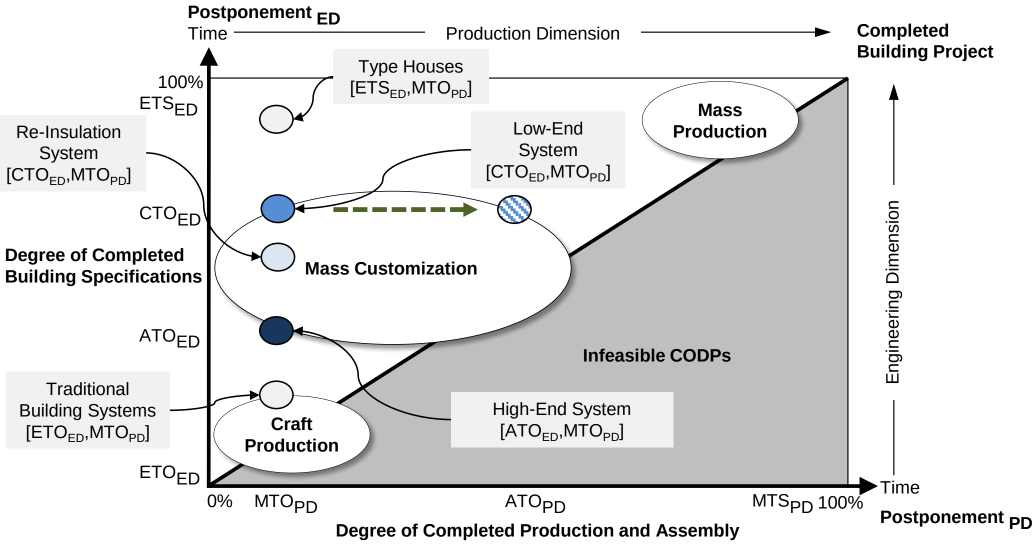

Figure 7: Platform leverage strategies for the HPC portfolio

Apart from economies of time, with the platform strategies the company is bridging the paradigm of delivering the optimum cost-value relation for each HPC product family. Figure 8 illustrates the impact the utilized platforms have on the accumulated cost throughout a building project. While the higher flexibility of the High-End system results in a relatively high cost structure which is close to the traditional building systems, it focusses on generating higher margins through an improved value proposition. An increase in material costs is compensated with saving in engineering, transportation and assembly, while the improved aesthetics and material properties add additional value to customers. Similar to car manufacturers, these Re-Insulation and Low-End system benefit from adapting product innovation, production technologies as well as better utilized resources during transportation and assembly of the High-End system to constantly improve their platforms. Being stronger concerned with offering competitive prices, the two families focus on reusing their assets along building projects, where non-value adding variety is reduced to a minimum. This enforced simplicity for example lowers the cost of a Low-End building to price points which are compatible with slack dwellers in development markets, yet using comparable materials and product quality as the High-End system.

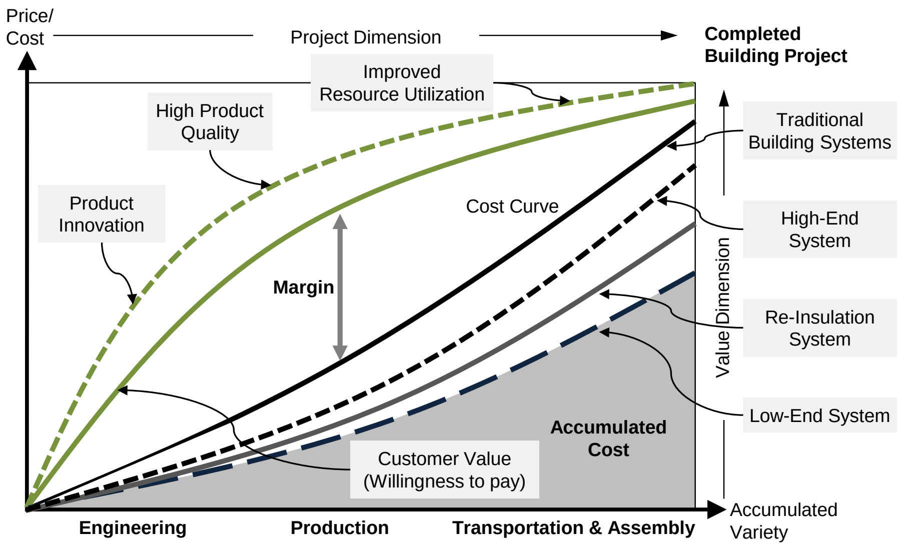

Figure 8: Economic implication of the HPC platforms in the case company

CONCLUSION

Research in construction has long been focusing on adapting concepts and methods from other industries such as the automotive industry to bring forward industrialization and to reach higher productivity levels. While the accommodation of lean principles has received much attention, fundamental methods for ensuring an efficient customization of buildings have mainly been neglected. Mass customization aims at bridging this gap of delivering customized products at near mass production efficiency. Successful mass customizers to be found in industry apply platforms as a means to acquire economies of scale while maintaining adjustable product structures, flexible processes and adaptive organizations. In addition they use product configuration systems around their platforms in support of their specification processes. Scholars approaching this topic have to adapt the two principles to the ETO situation in construction and to present practical guidelines for their implementation.

In addressing the two issues, we have presented a holistic view of platforms as a framework for understanding how mass customizing building projects is being facilitated. We use the precast sector as a representative industry to formalize the value chain of a building project in relation to the different manufacturing strategies according to CODP. By drawing upon theory in platform development, the creation of a product, process and logistics platform has been explained on the example of a building project. To create the right balance between commonality and distinctiveness, relationships between the platform domains as well as the connection to market requirements have been expressed through generic and matrix-based modelling methods. Then, we use the two-dimensional postponement of the CODP to synthesize the relevance of using configuration systems and to conceptualize the operational effects of platforms throughout the lifetime of a building project. Likewise, we introduce a cost-value concept to explain the related economic implications.

We employ a mixed-method research design, from both qualitative and quantitative sources, to collect evidence for the holistic view on platforms within the precast sector. This allowed us to explore in-depth how practitioners from the industry take up the platform concept, what challenges they face, as well as what benefits they realize. In our analysis we have compared three distinct platform strategies from a precast manufacturer compared to his otherwise traditional building projects. Each strategy was discussed according to both its operational as well as economic implications. Our results have shown strong incentives for implementing several feasible platform constructs within the precast industry. Moreover, we conceptually elaborated where companies can benefit from integrating configuration systems throughout the specification process of buildings, for which we recognize a huge potential for future research. Finally, we argued that utilizing platforms does not necessarily imply sacrificing design flexibility and customer value respectively in favor of efficiency, but rather involves the creation of an optimum cost-value relation for the target market segment.

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ARTICLE 7 VALIDATION OF THE REQUIREMENTS MANAGEMENT FRAMEWORK

Validation of the Requirements Management Framework for Construction Companies Offering Pre-defined Products

Will be submitted to the "Journal of Construction Management and Economics"

Validation of the Requirements Management Framework for Construction Companies Offering Pre-defined Products

Michael Wörösch

(Corresponding author, mailto:mwch@mek.dtu.dk, +45 27 11 41 42)

Niels Henrik Mortensen

Department of Mechanical Engineering

Section of Engineering Design and Product Development

Technical University of Denmark

Produktionstorvet

Building 426

2800 Kongens Lyngby

Validation of the Requirements Management Framework for Construction Companies Offering Pre-defined Products

1. ABSTRACT

The Requirements Management Framework (RMF) that was presented in the article "A requirements management framework for construction companies offering pre-defined products [1]" was developed to counteract the current requirements management related challenges of construction companies identified through a series of interviews.

This article describes the validation of that framework. The validation was done on several levels: a) a theoretical validation, where different scenarios of using the framework were enacted and evaluated, b) conducting 13 expert peer reviews, where interviewed parties were asked to assess if the developed framework positively contributes to solving their challenges concerning requirements management, c) three companies and one expert in Switzerland were visited and requested to evaluate the applicability of the framework to their building projects, d) a test house, erected on the campus of the Technical University of Denmark to which the framework was applied.

The results of this work show that the framework does not only apply in theory, but in practice as well, as the framework was successfully applied to an actual building project. Now, for the first time, there is an end-to-end requirements management process available to the construction industry.

Key words: Validation, conceptual framework models, requirements management, construction

2. INTRODUCTION AND PROBLEM

As of today requirements management (Krönert even uses the term requirements engineering, defined as "the requirements process and requirements management" [2, page 72]) in the construction industry only partly exists. Evbuomwan et al. [3], as some of the few, are using requirements management in construction but chose in their work to mainly focus on customer requirements. In order to be able to develop optimal project-specific solutions other categories of requirements management (requirements engineering) need to be defined as well [2, page 71].

Categories that were identified as being necessary for having an end-to-end requirements management process in construction, but that currently are not described well enough [1], are: life cycle related requirements; requirements testing / verification / validation; project results analysis where results are compared to project goals; network related requirements; and the consideration of types of project. Further categories are described in [2, page 71, table 2].

Not having those categories defined and well described leads to poor project scope which in return leads to increased project cost and duration [4] or project failure and lack of implementation [5].

As the construction industry has profit margins often as low as 1-3% [6] and a low labour productivity compared to other fields [7], having an end-to-end requirements management process seems to be especially critical for this field.

Hence, with the intention of filling those gaps and thereby counteracting the current requirements management related challenges of construction companies, a requirements management framework was developed for the construction industry. This framework was validated on several levels and the validation results are presented in this article. The validation of the framework and the results of applying it to a building project are described in the sections "Validation of the requirements management framework" and "Discussion of results".

This article is structured as follows:
3. Literature review and state of the art, 4. Research and design methods, 5. The Conceptual requirements management framework, 6. Validation of the requirements management framework, 7. Discussion of results, 8. Conclusion and Future Research.

3. LITERATURE REVIEW AND STATE OF THE ART

This section briefly describes some of the main contributors to this research, and summarizes the status of
the field.

When creating the RMF the consulted literature mainly focused on requirements management, systems engineering, construction, and framework models [1].

For being able to write an article about validating this framework the literature search was conducted as follows:

1) A check for any new, relevant publications concerning construction and infrastructure management in construction, frameworks, and requirements management in construction since [1] was written was made
2) An extended literature search to cover validation, validation of theoretical models, validation of qualitative models, and systems validation was done. Some of the articles used as a fundament to write [1] also have sections on validation

The following was found relevant during the literature search and was therefore used as base for the current article:

Arayici et al. [5] write about a requirements engineering framework for integrated systems development for the construction industry. Although the main focus of the article is systems development, it is related to the construction industry, project life cycle oriented, and describes some of the risks and success factors related to requirements engineering.

Yu and Shen [8] seek to discuss the so far incomplete requirements management process in the construction industry by highlighting the current limitations and advocating addressing the need for a practical framework for facilitating the implementation of requirements management. They also state that “due to increasing complexity in construction projects and greater expectation of the clients on project performance, the management of … requirements becomes a complex process which requires a systematic procedure to tackle it” [8]. In their literature review Yu and Shen describe nine problems and solutions of requirements management.

Jabareen was, in his article “Building a Conceptual Framework: Philosophy, Definitions, and Procedure” [9, page 54], giving a high level description of how to validate a conceptual framework model. The research described in this article follows Jabareen’s description.

The validation of the Value Based Requirements’ Risk Management (VRRM) process model as described by Basit et al. [10] was a source of inspiration for how to structure an article about the validation of a qualitative framework (model).

A vital article describing many ways of validating a model (in the context of validation the RMF is considered a model) and giving relevant definitions of validation, verification, and related terms was written by Edward J. Rykiel, Jr. His article “Testing ecological models: the meaning of validation” [11] was key for the validation of the framework.

Elliot G. Mishler [12] gives a new definition of the term *validation*. In his paper “Validation in Inquiry-Guided Research: The role of exemplars in Narrative Studies” he proposes an approach to the problem of validation in inquiry-guided studies. Mishler relies on Kuhn’s [13, pages 198-204] concept of exemplars. As the first of the three exemplars that he describes in his article is very close to the authors’ research, Mishler’s article was found particularly relevant.

Krönert [2, page 69] describes the validation of system input and output, and the validation of the process of finding requirements. In his thesis Krönert often refers to Girmscheid [14], who divides validation into an internal and external validation. Both authors are considered in this article.

4. RESEARCH AND DESIGN METHODS

This section describes the research methodology that was applied when developing and validating the RMF.

In [1] the research methodology was described up to and including the point of the first application of the RMF to a case project and a first presentation of the framework to selected stakeholders. For that four companies and one authority were chosen.

This article ties on to that work. Since [1] was written a lot of focus was given to the validation of the framework. Method-wise the validation was done by:

- Doing theoretical walkthroughs of the framework using different scenarios
- Conducting expert interviews
    - Presenting the framework to staff of additional companies in Denmark
    - Re-visiting previously interviewed stakeholders. In follow-up interviews they were asked for their opinion about the framework and if their requirements management related problems were resolved by use of the framework. They were also asked if the framework, in their opinion, is working and is operational
    - To round up the expert interviews the framework was presented to academics at the Eidgenössische Technische Hochschule (ETH) and industry experts at companies, all in Zurich, Switzerland. These were selected, as the construction industry of Switzerland seems to be rather advanced in comparison to Denmark, especially in terms of infrastructure management
- Building a test house and applying the framework to the building project
- Currently the framework is being applied to another building project, selected and made available by the management of the case company [1]. That building project is not described in this article

During the course of each of the above actions, opportunities for updating the framework were identified through an analysis of the data gathered during the respective action or directly pin-pointed by interviewees and users of the framework. The acquired information was used to update the framework. This is shown as the second from bottom step of Figure 1.

Following the update of the framework the, in this research gathered fresh knowledge, was disseminated in order to contribute to theory in the domains of requirements management in construction, framework models, and validation of qualitative models. Method-wise, Figure 1 depicts the steps that were gone through with when making and validating the framework. Please note that a short analysis of new information that potentially could make it necessary to update the framework was done at the end of each step of the framework. The reasons for showing “First analysis" and "Full analysis" as steps of the framework are that more resources were used for those analyses than the analyses of the individual steps as well as higher detail of analysis.

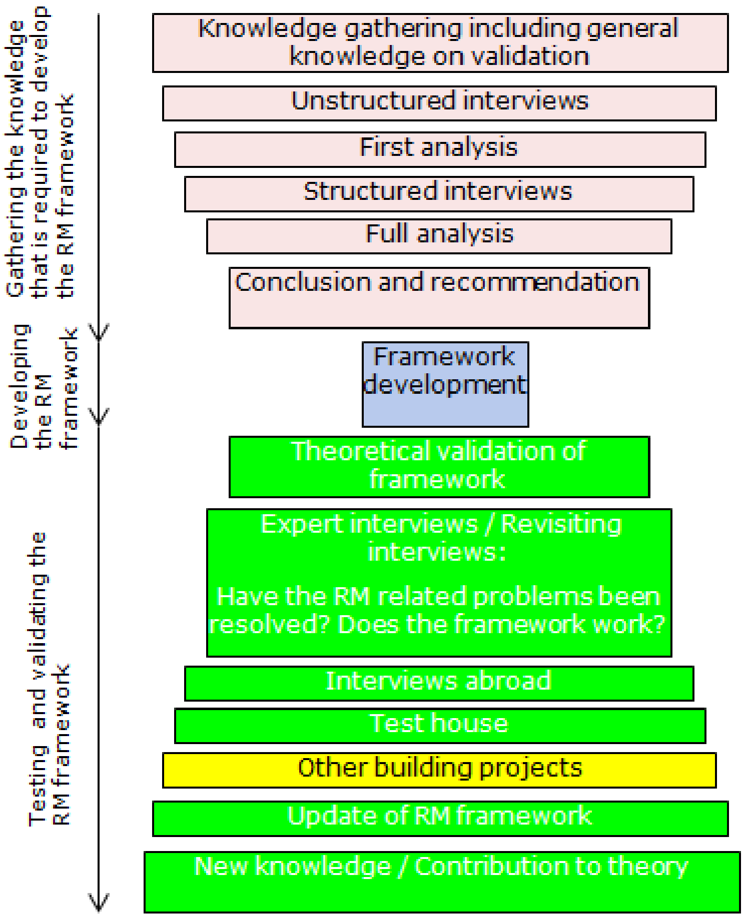

Figure 1: Research methodology – steps for making and validating the framework

The following section gives a brief summary of the RMF that was described in [1].

5. THE RMF

This section gives a brief summary of the RMF [1], its background, and relevant information concerning it.

The RMF was created in order to counteract the requirements management related challenges stated by industry experts of the Danish construction industry and those discovered when analysing the conducted expert interviews. The framework is intended to help project- and requirements managers in construction in managing the requirements they encounter in their building projects, end-to-end.

The framework provides a structured approach for identifying, documenting, testing, verifying, and validating the requirements that are relevant for a building project by guiding the user through some logical building blocks (BBx) as presented in Figure 2. One of the strengths of the framework is linking of the requirements of a project to goals and checking that those goals actually are achieved at the end of the project. The framework is still on a conceptual level and as part of future research the framework will be made operational with checklists per building block and project phase. Nevertheless the authors recommend that any construction project of over €10M should adopt the full framework as applying the framework is expected to result in big savings in terms of both time and money.

When developing the framework, knowledge was, apart from interviews and domain literature, also drawn from IEEE [15] standard 1233-1996 [16] as well as the disciplines of systems engineering [17, 18] and project management [19].

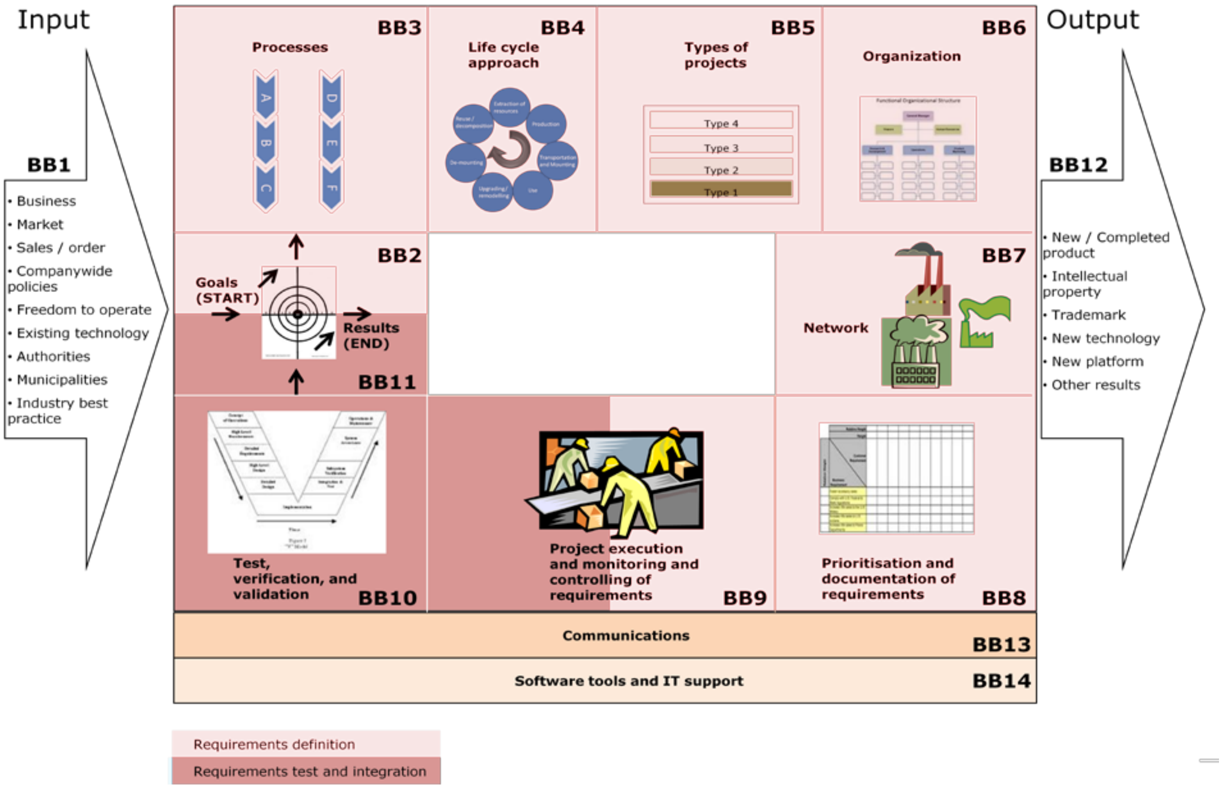

Figure 2: A requirements management framework for construction companies offering pre-defined products [1]

The validation of the framework resulted in several updates of it. Those updates are described in section 7 "Discussion of results".

6. VALIDATION OF THE RMF

6.1 General

This section describes in detail the validation of the requirements management framework. The section provides several definitions of the term *validation*, a description of the approaches used for validating the framework, as well as answers to *why*, *what*, and *how* in relation to the validation.

6.2 Definitions

This sub-section provides some definitions for understanding the validation and thoughts behind the framework, described in this article.

Rykiel [11] defines the term *validation* as: "Validation is a demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". In his article he mainly focuses on validation in the context of simulation models. As the RMF only to a very limited degree can be considered a simulation model, one might question the decision to base part of this research on [11]. Nonetheless, Rykiel provides a lot of elements and thoughts, as e.g. a description of different (model) validation concepts and definitions of relevant terms as *verification*, *calibration*, *credibility*, *qualification*, that partially could be used when validating the framework.

Another definition of *validation* can be found in [12]. Here it is (re-)formulated as "the social construction of knowledge." With this reformulation, the key issue becomes whether the relevant community of scientists evaluates reported findings as sufficiently trustworthy to rely on them for their own work. Mishler argues that for "inquiry-guided research the standard approach to validity assessment (e.g. measuring variations on quantitative dimensions or "testing" the significance of the findings with statistical procedures) is largely irrelevant to our concerns and problems" [12]. As a lot of the described research was inquiry-based, Mishler was considered to a large extend.

When reading this section about validation the reader should keep in mind McCarl: "…concepts like validation have strong *subjective* elements…" [20]. In other words: What passes validation at one place could easily be rejected at other places (research communities).

Another useful definition is *conceptual validity* which means "that the theories and assumptions underlying the conceptual model are correct, or at least justifiable, and that the model representation of the problem or system, its structure, logic, mathematical, and causal relationships, are reasonable for the model's intended use" [11].

6.3 Validating the RMF – the applied approaches

Jabareen [9] writes "The question is whether the proposed framework and its concepts make sense not only to the researcher but also to other scholars and practitioners. Does the framework present a reasonable theory for scholars studying the phenomenon from different disciplines?

Validating a theoretical framework is a process that starts with the researcher, who then seeks validation among “outsiders””. This approach was followed when validating the framework. Since Jabareen’s description is on a rather high level, a more detailed description of what was done validation-wise is needed:

The requirements management framework was validated on several levels. 1) First a theoretical validation of the framework was done, where different scenarios of using it were examined. 2) Second expert peer reviews, where interviewed parties were asked to assess if the developed framework positively contributes to solving their challenges concerning requirements management were conducted. 3) Then companies outside Denmark were visited and requested to evaluate the applicability of the framework to their building projects. 4) Thereafter a test house was erected on the campus of the Technical University of Denmark that the framework was applied to.

Rykiel refers to a series of validation procedures [11]. Four of his validation procedures were applied to this research:

“Traces: The behaviour of specific variables is traced through the model and through simulations to determine if the behaviour is correct and if necessary accuracy is obtained”.

“Extreme-condition tests: The model structure and output should be plausible for extreme or unlikely combinations of factors in the system. This test reveals if behaviour outside of normal operating conditions is bounded in a reasonable manner”.

“Face validity: Knowledgeable people are asked if the model and its behaviour are reasonable. This test suggests whether the model logic and input-output relationships appear reasonable ‘on the face of it’ given the model’s purpose”.

“Multistage validation: Validation methods are applied to critical stages in the model building process: (1) design: develop the model’s assumptions based on theory, observations, general knowledge, and intuition; (2) implementation: empirically test the model’s assumptions where possible; and (3) operation: compare the input-output relationships of the model (compare theory and output, e.g. test house) and the real system. The three validation steps correspond roughly to conceptual, data, and operational components”.

Rykiel’s validation procedures can be used to express what was done on validation stages 1) to 4). Table 1 shows a mapping of the executed validation of the framework to defined validation procedures.

Table 1: A mapping of the executed validation of the framework to defined validation procedures

		Performed validation			
		Theoretical validation	Expert peer reviews	Expert peer reviews abroad	Building project
Validation procedures as described by Rykiel	Traces	X			
	Extreme-condition tests	X	X	X	X
	Face validity		X	X	X
	Multistage validation	X			X

6.4 Why, what, and how to validate

6.4.1 Why validating this framework?

There were several reasons for validating the framework. The following needed to be examined according to findings in previous sections:

- Does the framework work?
- Is the framework effective?
- Are there any advantages / disadvantages connected to using the framework? Indications could be a changed spending of time and money
- The usability of the framework; i.e. is the user able to use the framework without any problems?
- Were the requirements management related challenges of the case company resolved or at least improved?
- Generalizability – can the framework be applied to other building projects?
- How does the framework perform outside its intended area of use?
- Is the framework considered good enough so others dare base their work on it – industry professionals as well as academics?

6.4.2 What and how to validate?

This sub-section describes the performance requirements of the framework, what was validated, and how that validation was done.

"Validation is not a procedure for testing scientific theory or for certifying the 'truth' of current scientific understanding, nor is it a required activity of every modelling project. Validation means that a model is acceptable for its intended use because it meets specified performance requirements. Before validation is undertaken, (1) the purpose of the model, (2) the performance criteria (the criteria the model must meet to be declared acceptable for use), and (3) the model context (in which it is intended to operate) must be specified" [11].

The purpose of the framework is, as stated in section 5, to help project- and requirements managers in construction in managing the requirements they encounter in their building projects, end-to-end.

The following performance criteria were defined for the framework by the authors and staff of the case project:

1) It has to support the management of requirements for all life cycle phases of a building (End-to-end)
2) It has to guide the user to state goals and sub-goals at the beginning of a building project
3) It has to make sure that at least priority “1” requirements are in fact tested, verified and validated; i.e. the framework supports that requirements are incorporated in the right way, that the requirements actually meet the users’ needs, and that the specifications were correct to begin with
4) This means that acceptance criteria must be defined and checked for requirements
5) It facilitates that latest time at the end of a building project the results of implementing requirements are compared to the goals and sub-goals that were stated at the beginning of the same building project
6) It helps making sure that the (organizational) network of the company is considered when managing requirements
7) It makes certain that the different types of projects a company is running in parallel to their building projects are considered as well
8) When applying the framework to an actual building project (here the test house) the requirements management related challenges of the company applying the framework are resolved or at least improved
9) It has to be considered *effective* by its users
10) It has to be considered *useful* by its users
11) It is accepted by academics and industry practitioners, e.g. they positively consider applying it to other building projects

The operational context of the framework:

It is intended to be used on building projects. The development of the framework was originally initiated to support the project manager of the case project in managing requirements on building projects that were initiated to produce single family houses with a maximum of 2 floors. Later the scope was extended to buildings in the range from single-floor family houses over large housings to 200.000 m^2 office buildings as those are produced by the interviewed companies.

The framework is also proposed to be used on building projects where products, product platforms, and technology are being developed in parallel.

Now, that a common ground has been established this section continues with a description of what was validated and how the validation was done. As shown in Table 1 the following kinds of validation were done:

<u>Theoretical validation</u>

The first validation steps of the framework were of internal nature. Those steps were taken when the focus of the framework merely was to help the project manager of the case project to manage his requirements better. During this validation it became clear that some basic processes, which are successfully used in other industries, simply have not found their way to the construction industry, yet. A literature review (See e.g. Fernie et al. [21], Krönert[2], and Yu and Shen [8]) on the subject of requirements management in construction endorsed this state as they confirmed that requirements management to a large extend is missing in the construction industry.

This situation led to other construction companies in Denmark being visited by the authors. The hypothesis was that at least construction companies running many small or few large construction projects resulting in a yearly turnover of 100 M€ must fully or partially have systems and processes in place for managing requirements as large amounts of money are at stake in case of poor scope management.

Before visiting some of those construction companies the “Traces” and “Extreme condition tests” were performed for the first time. The variables used to do the “Traces” were some of the performance criteria that were described in section 6.4.2. Those variables were applied to the kinds of projects that are typical for the case company.

For the “Extreme condition tests” the identified scenarios below were chosen, as they only rarely occur. The fact that only very few construction companies are doing research and development, which is required in order to get into the tested extreme conditions, was e.g. backed-up by Tim Mander, the Minister for Housing and Public works of Queensland, Australia, who explained during a key note speech at the World Building Congress 2013 that only 1% of all Australian construction companies are doing research.

The framework was run through simulations of the following cases:

1) Building project and technology development project
2) Building project and product development project
3) Building project and product platform development project
4) Building project, product development project, and product platform development project
5) Building project, technology development project, product development project, and product platform development project

Case 5) is here considered the most extreme case that will only occur in very few construction companies. Nevertheless, that is what the case company is doing, successfully.

The first part of the multistage validation "develop the model's assumptions based on theory, observations, general knowledge, and intuition" was part of the theoretical validation. In this stage the assumptions that the framework was built upon were listed for later checking.

As part of the theoretical validation *non-performance* of the framework was considered: Here the scenario of applying the framework to a tunnel project was covered by interviewing an industry expert.

A theoretical validation of each building block was also done by the project manager and some of the key people of the case project. Subsequent to the completion of the test house, the results of each building block were re-visited and compared to reality.

<u>Expert peer reviews</u>

For writing [1], 32 expert interviews were conducted at 12 companies and one authority in Denmark. At that time the framework was reviewed by four companies and one authority. Since then, some follow-up interviews were done and additional companies, dwellers of houses that had already been built by the case company, the project manager of the case project and test house, and several members of the project team erecting the test house were interviewed in Denmark.

Apart from the dwellers, all interviewees were asked:

- If the framework is grounded in reality
- If the framework works in their opinion
- If the framework solves their requirements management related issues
- Whether they would use it
- What should be changed / improved with the framework

All review comments were made anonymous, put into the same document, colour coded, grouped, and analysed. The reviews have, together with the data analysis, provided valuable input for improving the framework to better reflect reality.

Expert peer reviews abroad

Some interviews / reviews of the framework were done in Zurich, Switzerland. For that two construction companies, that are market leaders within their field, and an industry specialist were visited and asked the same questions as the interviewees in Denmark.

To gain an extra dimension on this research an expert in constructing tunnels was interviewed about the applicability of the framework in order to find its boundaries. He was asked to evaluate the framework by theoretically applying it to a typical street tunnel project.

The interviews conducted in Switzerland were analysed and then compared to the interview results gained in Denmark.

Building project – test house

The practical validation of the framework was done by applying it to a building project of a two floor test house that was built on the campus of the Technical University of Denmark. The main reason for building the test house was not to test the framework but to do long term data logging of the strength / shrinkage of the walls and the performance of insulation material and piping as new technology was used on the test house. Testing the framework was in this context a by-product. The test house can be seen in Figure 3.

Figure 3: Test house on the campus of the Technical University of Denmark

Each building block of the framework was applied to the test house building project. Due to the consistent use of the framework, each building block of it, and the framework as a whole, could be validated once the test house was finished.

When validating processes on building projects some practical challenges do exist:

1) [22] states: the prototype of a building is the actual building. The performance of the framework can therefore not be validated by comparing the results of applying it to the prototype and the finished building
2) It is hard to measure and quantify the actual effect of a qualitative model. Apart from that one has to account for a learning curve when e.g. making single family buildings within the same company using the same people

Being aware of those challenges the framework was validated in a different way. As suggested by the interviewed Danish authority the framework was validated on the test house building project by evaluating a) if the developed framework as a whole was positively contributing to solving challenges concerning requirements management and b) each building block individually and rating it between "+" to "+++" for an improvement in the consumption of time and money, compared to projects where the framework was not used. The ratings "-" to "---" were used accordingly where applying the framework led to an increased spending of time and money. Here it is important to distinguish between using the framework for the first time and using the framework on sub-sequent projects. This subjective validation was done by the project manager and some selected key people and is shown in Table 2 in section 7.

As recommended in [11] the second stage – "implementation" of the multistage validation was done on the test house.

Another qualitative validation was done by comparing the results of applying the framework to the test house building project and comparing them to the performance of previous building projects (also single family houses of approximately same size and complexity).

In the following section the results of the different kinds of validation as well as using the framework as a whole are described. The results will be presented in the same order as the validation types in section 6.

7. DISCUSSION OF RESULTS

The "Discussion of results" section first describes the main results that were found when validating the requirements management framework in different ways and then concludes with a sub-section on generalizability and the impact of the framework.

7.1 Validation results

Theoretical validation

The theoretical validation of the framework was done in several ways. First two of the previous building projects of the case company were analysed (internal validation) for how requirements were gathered, documented, and managed. The analysis also had the purpose to find the typical situations [23] of the case company with regards to requirements management. At that time the framework already showed the first promising features but did not work, yet, as necessary tests, acceptance criteria of requirements, and “extreme” cases were not addressed. Besides, the framework was not covering end-to-end. When looking at project data from the past, those inadequacies have been a consistent challenge for the case company.

The second step of the theoretical validation was to compare the results of the framework to literature published in academia or by industry professionals. Here almost no help could be found at all. From an operational point of view the most helpful literature was published by INCOSE [17, 18, and 22].

The third step was to approach other construction companies in a series of interviews. The interviews had the purpose to find out how requirements management is done in the construction industry in Denmark. During those interviews a generic process for managing requirements surfaced and the individual building blocks of the framework were developed but not fine-tuned (order and content still had to be improved), yet.

As step number four the framework was, in that state, re-applied to the already analysed projects of the case company with the result that the in the beginning of this sub-section mentioned shortcomings were addressed successfully. An order of the individual building blocks that appeared to be generic was found and the context of each building block was described (still on a conceptual level).

After step number four the framework was baselined and released in a version 1.0. This version was then used to do “traces” based on the in section 6.4.2 described performance criteria. For that the performance criteria 1) to 7) were taken one at a time and the framework was validated for fulfilling those individual performance criteria. Thereafter the framework, together with the individual performance criteria, was theoretically applied to a previously analysed building project of the case company and the performance of the framework was evaluated based on that. Founded in those results the content of the building blocks of the framework was then changed (mostly extended).

“Extreme condition tests” were done by theoretically applying the framework to the 5 cases that were identified as extreme cases. After the “traces”, the framework was able to handle all identified extreme cases. This was as expected as the framework was designed for handling them.

Non-performance of the framework: So far the framework was successfully applied to pure construction projects where buildings were erected and to construction projects (still buildings) in combination with development projects of different sorts. In theory the framework is not expected to work for other kinds of projects or outside the construction domain. As part of the non-performance testing of the framework a theoretical application to a street tunnel project was done. This application resulted in the framework being “applicable”, which was unexpected. In order to find the limits of the framework further theoretical applications have to be done. An IT project has been selected for future non-performance testing.

Executing the “traces” and “extreme condition tests” considerably contributed to the first part of the “multistage validation”, where the framework’s assumptions were developed based on theory, observations, general knowledge, and intuition. In fact conducting the multistage validation only gave very little new insight and results from a theoretical perspective but had the advantage of questioning the framework’s assumptions. The second part of the “multistage validation” was done during the test house building project and will be described below. The third part was skipped as it is targeted at operations, which is outside the scope of the framework.

<u>Expert peer reviews in Denmark</u>

For developing the framework 41 interviews were conducted in Denmark. The interviews were held at one university, 12 companies, one authority, and with two dwellers.

For doing the face validity of the framework in Denmark industry experts from 7 companies and one authority were visited. On top of that the project manager of the case project and test house building project and four members of the test house building project team were interviewed.

During those interviews many comments were received. Those comments were, to the extent possible (e.g. not contradictory, not company specific), incorporated into the framework. Most updates to the framework happened during the first third of the interviews. The evolution of the framework can best be seen by comparing Figure 2 to Figure 4.

22 of the interviewees were of the opinion that the process of requirements management needs to be improved in construction. 16 of the interviewees said that there is a need for an end-to-end process for managing requirements in construction. None of the interviewees had seen an end-to-end framework for managing requirements in construction before.

Without any exception, the interviewees were very forthcoming when providing the opportunity to conduct an interview and when handing over data. An indication of the importance of the area of requirements management in construction is the fact that in all except two of the companies that were interviewed, either the owner or the responsible vice president were participating in the interview. In the remaining two companies a project manager and a subject matter expert participated.

With no exclusion the interviewees that were introduced to the framework stated that the framework is grounded in reality and seems to work in their opinion. Only two of the companies stated that they would not use the framework for reasons of 1) already having a system in place that they did not want to replace and 2) not using processes that are not required by law at all as this, in their opinion, diverts focus from the customers and craftsmen. The other companies stated that they would use the framework in full or to a large extend. Two of the Danish companies and one authority, consisting of academics and practitioners, already asked about the implementation of the framework. Their wish to get the framework implemented and to base their work on it is a strong validation of the framework.

1 out of 13 interviewed persons that were introduced to the framework (8 by face validity and five by actually applying the framework) acknowledged that the framework fully resolves the requirements management related issues that they had stated. 10 out of 13 interviewees reckoned that the framework, to a large extend, solves the requirements management related issues that they are currently facing. None of the interviewed persons indicated that the framework does not resolve their requirements management related issues.

When walking through the building blocks of the framework the order of them was frequently discussed. Regardless the order of the individual building blocks in relation to each other each building block made sense and had its justification.

The interviews also confirmed that applying the framework is most beneficial for medium-sized and large companies running projects in the range of 10 M€ and above.

<u>Expert peer reviews abroad</u>

Three companies were interviewed in Zurich, Switzerland. The authors are aware of the fact that three interviews are not representative but believe in getting an indication of the applicability of the framework to another market and a different angle on requirements gathering and management in general. This additional angle was used for enriching the framework. The three interviewed companies were chosen due to their market leadership, expertise, accessibility and willingness to participate.

The three interviews had the following main results: All interviewed industry experts concluded that the framework is rooted in reality, useful, working, and covering the process of requirements management end-to-end.

Two of the interviewed companies stated that they would look into applying the framework as it facilitates planning and thereby contributes to shorter project times. The third company had a well working management tool in place facilitating the required core and supporting processes of requirements management and was therefore not interested in going further with regards to a potential implementation of the framework. None of the interviewees had seen an end-to-end framework for managing requirements in construction before – only elements of it. All three interviewed persons (two vice presidents and one project manager) considered the framework a good leadership tool supporting the flow of projects and confirmed that applying the framework makes most sense for medium sized and large companies as they tend to run the biggest projects. One interviewee stated that the framework facilitates continuous improvement and increases the quality of building elements and thereby the quality of the building.

During the interviews it was striking that compared to the interviewed companies in Denmark, a lot of effort is being put into planning, early requirements gathering and identification of risks. For that reason the Swiss interviewees e.g. stated that the network of a company (BB7) and even details as the level of education that people have in the area of a building site should already be considered before starting a project. The three Swiss interviewees stated independently, that customer satisfaction is their priority number one and other criteria as e.g. price, timely delivery or quality are of secondary nature.

There are, of course, many factors influencing the profit of a company but the fact that the lowest achieved profit margin during the past three years was 4% compared to the 1-3% the Danish companies are able to realize, gave food for thought.

<u>Building project – test house</u>

When building the test house shown in Figure 3 the RMF was applied to the entire project. This practical validation of the framework has given a series of results:

All building blocks of the framework could be applied and made sense where applied. The order of the building blocks was as shown in the framework (Figure 2) even though the framework allows the order of the building blocks to be changed where it is meaningful.

For evaluating the performance of the requirements management framework on the test house building project a comparison of the parameters time and money (most important parameter) was made to two of the case companies previous building projects. The expectation was that the test house building project will perform better in terms of using time and spending money than the two previous building projects it is compared to.

The first building project went for various reasons 300% over time and budget. This was regarded as extreme. But at the same time this was the first project where the case company used the new HPC material. Part of this project was also to get the new material fire safety approved which took several attempts and therefore took much longer than expected.

The second project was delivered in time and had a budget overrun of 30%, which was considerably less than the first project. The requirements management framework was not used on any of those two previous projects.

Concerning the test house building project: On completion of the test house an analysis of the project budget and time schedule showed that the time schedule was kept and the budget was exceeded by 20% even though many more challenges (e.g. the installation of several hundred sensors for measuring different parameters and the exceptionally problematic fitting of the roof) had to be coped with than on the two other building projects.

Comparing those three projects showed a further improvement in the case company's ability to deliver in time (more robust) and on budget (10%). Even though the skill to stick to a budget should be improved further. It is hard to exactly quantify how much the requirements management framework has contributed to this improvement. Nevertheless we dare to make the claim that using the framework and focusing on requirements management had a positive influence on the performance of the compared parameters. This claim is supported by project staff and described below.

When asking four selected project staff members of the test house building project about the results of applying the framework, the following was stated:

- "The use of the framework puts more focus on requirements management. As the benefit of using it is a better organization of the time available"
- "Using the framework results in requirements being more structured and divided into work packages. This leads to a faster execution of the project and a clear distribution of responsibilities"
- "Applying the framework at the beginning of a project gives less problems at the end of the project due to requirements management already being applied"
- "The framework supported a constant update of goals, strategies, and roadmap as the project staff wanted to use requirements management as optimal as possible"

None of the interviewees said that they would not use the framework again. Three of the interviewees stated that they should have known the framework earlier as this would have helped them in earlier projects. All four interviewed staff considered the framework as a useful help in their work.

When questioning the project manager about the performance of the requirements management framework at the end of the test house building project, he confirmed that the framework as a whole positively contributed to the spending of time and money. He also highlighted that the flow of the framework is aligned with the flow of the project and that the framework had forced some structure into the scope management of the test house project. Altogether he evaluated that the requirements management related challenges of the case company have been mitigated. For completely resolving them more training is needed and the attitude of the staff has further to be improved.

The second part of the multistage validation “implementation”, that is used to empirically test the framework’s assumptions where possible, was done at the same time as the evaluation of the effect of each building block and the framework itself. The evaluation of the effect was performed by the project manager and four selected key people and is shown in Table 2. The rating is as described in 6.4.2

Table 2: An evaluation of the effect of the individual building blocks of the requirements management framework on the consumption of time and money on the test house building project

	Expected (Beginning of project)	**Expected (Entire project)**	**Test house (First project)**	**Subsequent projects**
BB1: Input	-	+	+++	+++
BB2: Goals	--	+	+	++
BB3: Processes	+	++	++	++
BB4: Life cycle approach	-	+	+	+
BB5: Types of projects	-	++	+++	+++
BB6: Organization	-	+	+	++
BB7: Network	+	++	++	++
BB8: Prioritization and documentation of requirements	---	--	+++	+++
BB9: Projects execution and monitoring and controlling of requirements	--	-	+	+
BB10: Test, verification, and validation	--	--	+++	+++
BB11: Results	--	-	--	-
BB12: Output	+	++	+++	+++
BB13: Communications	-	-	++	++
BB14: Software tools and IT support	+	+	+	++

The “Expected (Beginning of project)” column reflects the project staffs immediate anticipated effect of the framework and each of its building blocks when the framework was being presented to them. The “Expected (Entire project)” column shows the project staffs theoretical evaluation of the effect of each building block for the entire project once they were thoroughly presented to the complete framework. The “Test house (First project)” column shows the evaluation of the project staff *after* the practical implementation of the framework at the end of the building project. The “Subsequent projects” column reflects their anticipation of the effect of the individual building blocks for subsequent projects. Here they took into account the implementation of some software tools to better support the use of the framework and a learning curve.

The results of the validation of each building block upon the completion of the test house were compared to the expected results of each building block gained at the theoretical validation. Whenever estimates were off the deviation was used as a learning point and new knowledge was added to the framework.

To finish the above described theoretical validation of the framework the performance criteria 8) – 11) that are listed in section 6.4.2 were re-visited and analyzed once the test house building project was finished. The result of this analysis is that those criteria were fulfilled.

7.2 Results of the validation approach

When validating the framework the approach was to apply different kinds of validation (as described in section 7.1) in order to get a validation of the framework from theoretical and practical angles. The authors believe that the validation results thereby become more reliable. Apart from that literature [e.g. 11, 12, and 24] has shown that a mixture of theoretical and practical validation is good practice when validating models.

The results of the different types of validation that were performed on the framework led to the same conclusion: the framework works well in theory and in practice on the types of building projects and tasks it was intended to. The framework also seems to perform fine in the validated extreme cases and sample projects abroad. Therefore the approach of applying different kinds of validation was considered a success.

At the moment, the use of requirements management framework in construction is at its very beginning. Once the use of such frameworks is more widespread “event validity” and computer simulations of the framework that is compared to reality can be added to the types of validation that can be used.

7.3 Validation of the effect of the framework

When validating the effect of the framework it was shown that the interviewees believe in the framework having a positive effect on managing their requirements as the requirements management related issues they normally face at work were addressed; i.e. those issues were either resolved or the situation had at least improved.

Interviews have shown that especially medium-sized and large companies (measured in size of biggest projects in m^2 and €, size of company, and turnover) will see a positive effect when using the framework. Interviews also have shown that small companies are reluctant to applying the framework “as it diverts focus from the customers.” For the same reason those small companies stated that they are reluctant to any kind of process that is not required by law.

Furthermore it was demonstrated that the framework had a positive effect on the test house building project as the process of gathering and managing requirements was more structured as it otherwise would have been as well as time and money was saved compared to analysed earlier projects of the case company.

Altogether the performance criteria listed in 6.2.4 were met.

In conclusion to the validation of the framework the authors make the claim that 6 out of the 9 problems of requirements management in construction, as presented by Yu and Shen [8], are directly addressed by the framework and the three remaining problems are supported by the framework by providing a useful structure and a number of recommendations.

7.4 The updated RMF

During many of the conducted interviews and reviews proposals were made for updating the RMF so it better fits with the organization of the interviewee / reviewer. In the course of the analysis of the data gathered at the interviews more suggestions surfaced. Not all proposals could be combined with each other as some were contradictory (e.g. the naming conventions of certain building blocks or the content of building blocks). In those cases the solution favoured by the majority was chosen.
Some companies as e.g. one of the largest construction companies in Denmark expressed the wish to also use the framework for different purposes namely to push the company towards more innovation and to use the framework for conversations with customers to explain the flow of (customer) requirements and for teaching at internal courses. Such wishes were considered by-products and no special efforts were made to facilitate them when constructing the framework.

When comparing Figure 2 – the originally proposed framework for managing requirements in the construction industry – to Figure 4 – an updated version of the same framework, the following main changes were made to the framework:

- BB1: The term “Market” was changed to “Market / Demand” as some building projects are initiated based on a political decision rather than based on market demand
- BB1: The “Network” that is described in BB7 has already to be considered in BB1
- Risk Management was considered very important throughout the whole building project therefore it is now part of all Building Blocks (BBx) except for BB12. It was interesting to

observe that none of the asked construction companies seems to focus on risk management from BB12 and onwards

- The “Life cycle approach” and “Types of projects” have swopped places
- A discussion of what life cycles are relevant to a building project is now already initiated in BB1
- Now there is even more focus on acceptance criteria in BB8
- It is now acknowledged that Operations and Maintenance (O&M) start at BB12. The framework does not cover O&M and therefore stops at the end of BB12
- By updating BB9 it was acknowledged that a few construction companies are making mock-ups before building
- The empty white rectangle in the middle of the framework is now not empty anymore. This was disturbing for many readers
- BB12 is now coloured. Several times it was pointed out that the white colour is misguiding

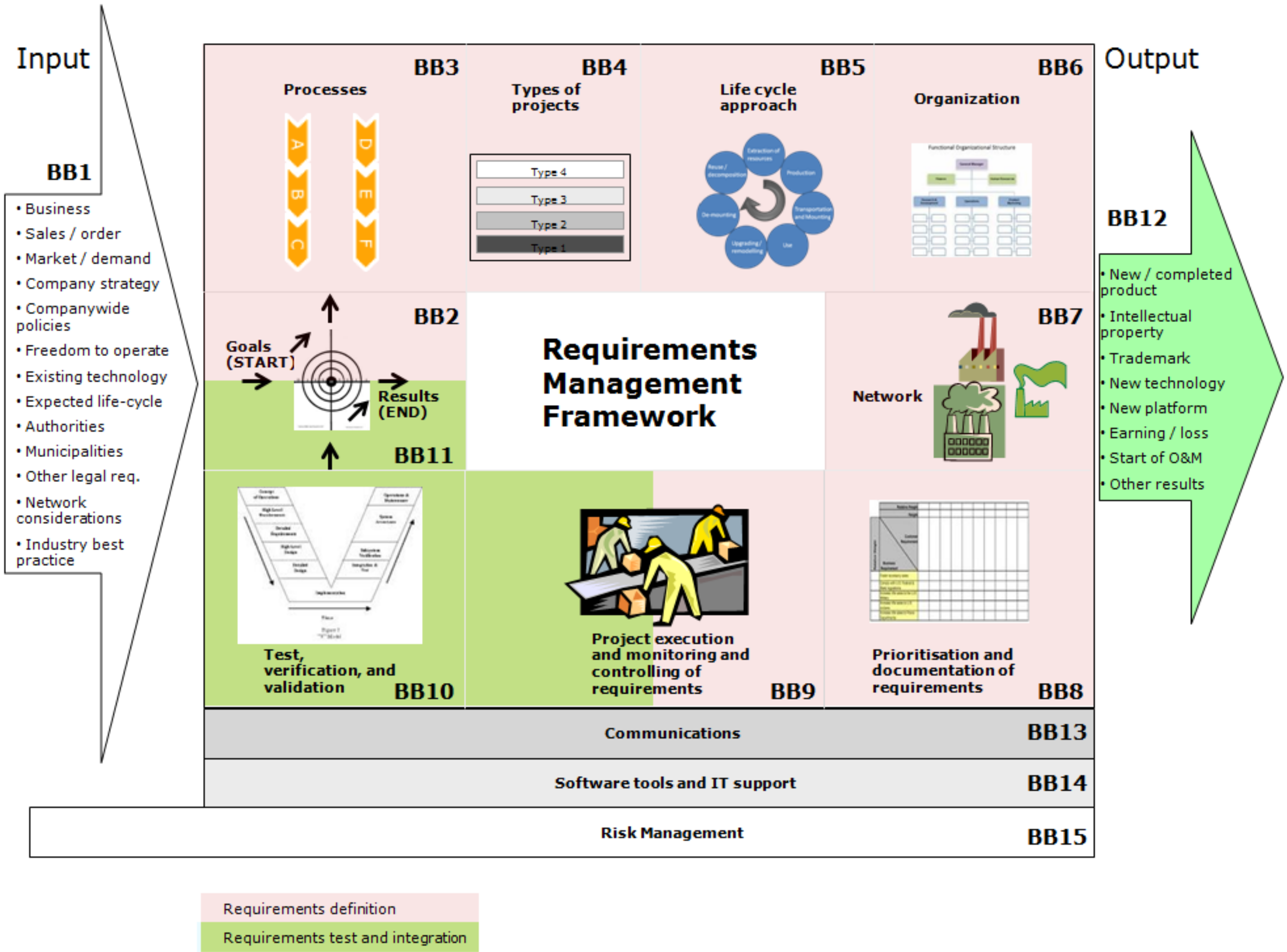

Figure 4: An updated version of the proposed framework for managing requirements in the construction industry

7.5 Generalizability and impact of the framework

7.5.1 Generalizability of the framework

No claim can be made that the framework can be applied to all kinds of building projects in construction. What so far was done successfully was applying the framework to the test house building project and to the extreme cases of the case project.

Apart from that the face validity done at the expert peer reviews in Denmark and Switzerland has confirmed that the framework can be used on building projects of sizes between 100 m^2 to 200.000 m^2 and cost between 13.400 M€ to 670 M€.

The framework was even – in theory – applied to a project building a street tunnel. As the street tunnel building project differs a lot from single family houses and industrial buildings non-conformance of the framework would have been a possibility. But it turned that out the framework performed well on this kind of building project. As a consequence the framework will be applied to non-building projects outside construction to find its boundaries. A first indication is that the framework supports building and research and development projects well – regardless the field of use.

7.5.2 Implications of the framework

The existence of this framework has the following implications:

- For the first time project- and requirements manager of construction companies have a tool available that helps them manage their requirements end-to-end. This means that there is now a “true” requirements management (as recommended by INCOSE and PMI) process available to them
- Many of the requirements management related challenges that construction companies are facing today can be overcome by following the framework
- Projects having a structured scope management are more likely to stick to their budget and time schedules. Also the quality is likely to increase and the number of risks is expected to decrease

8. CONCLUSION AND FUTURE RESEACH

In 2013, Yu and Shen [8] advocate that the requirements management processes in construction are having limitations and a practical framework for facilitating the implementation of requirements management in the construction industry is needed.

The RMF that was described and validated in this research is a step in that direction as a lot of input from practitioners was considered. What residue is making the RMF operational with checklists per building block and project phase.

The validation of the effectiveness and generalizability of the RMF was done in several ways. The main results of that were:

- Face validity gave a confirmation that the framework as such is effective on projects sizing from 100 m^2 to 200.000 m^2 or 13.400 M€ to 670 M€ respectively
- Expert peer reviews conducted in Denmark and Switzerland established that the framework is grounded in reality and addresses the requirements management related challenges that the reviewers encountered in their work. Furthermore the framework is not limited to mainly focusing on customer requirements but has an end-to-end approach covering the whole life cycle of a building requirements-wise
- The successful application of the framework to the test house building project. Following Mishler's new approach to validation [12] the quantitative validation of the framework that was done was very limited. Instead a qualitative analysis of the framework in its entirety and a qualitative analysis of each individual building block of the framework was done with encouraging results. The most encouraging result was that two of the Danish companies and one authority, consisting of academics and practitioners, already asked about the implementation of the framework. This was a strong validation
- The framework was applied to extreme conditions, as described in section 6.4.2, with the conclusion that the framework also works under those
- A theoretical application of the framework to a street tunnel building project was done to find the boundaries of its application. It turned out that the framework could be applied to this kind of building project as well

When re-visiting the, by Yu and Shen [8] presented, 9 associated problems of requirements management in construction from the literature review it is estimated by the authors that the framework directly addresses 6 of those problems. The remaining three problems are supported by the framework, however, e.g. the 'experience level of clients in requirements management' or 'the inadequate requirements effort throughout the life cycle' cannot be controlled by the framework but only supported by providing a useful structure and a number of recommendations.

In conclusion to the implications of the RMF, it can be stated that for the first time project- and requirements manager of construction companies have a tool available that helps them manage their requirements end-to-end. Simultaneously many of the requirements management related challenges that construction companies are facing today can now be overcome by following the framework.

The question that remains to be answered is if the maturity and will to improve requirements management is present in the construction industry.

8.1 Future Research

After having developed and validated the RMF the following areas of future research still have to be addressed:

- The framework has to be made operational with checklists per building block and project phase
- The framework has to be applied to further building projects in order to gather more data for the improvement of the framework. A meaningful building project for that could be the energy renovation of a building block consisting of several stories. Such a project could be provided by the case company
- The boundaries of the framework have to be identified by applying it to new kinds of projects

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DCAMM
Danish Center for Applied Mathematics and Mechanics

Nils Koppels Allé, Bld. 404
DK-2800 Kgs. Lyngby
Denmark
Phone (+45) 4525 4250
Fax (+45) 4593 1475
www.dcamm.dk
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